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ACOUSTIC EMISSION TESTING

OF

COMPRESSED GAS TUBE TRAILERS

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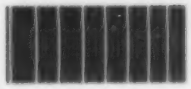

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D. Robert Hay

TEXTREND INTERNATIONAL INC.

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The contents of this report reflect the views of the authors and not necessarily the official view or opinions of the Transportation Development Centre of Transport Canada

Un sommaire en français de ce rapport est inclus avant la table des matières.

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Transportation Development Centre
Transport Canada
Montreal,QC
Mr. Sabounghi was the Scientific Authority representing the Transportation Development Centre on the project.

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Mr. Mohand Abdelli
Gas Technical Service
Canadian Liquid Air Ltd.
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Canadian Transport Commission
Ottawa, Ontario

Mr. Jean Bouchard
Mr. Walter Jancewicz
Mr. Herman Fortin
Dangerous Goods Directorate
Transport Canada
Ottawa, Ontario

Dr. Herve Barthlemy
DG\Direction Techniques
L'AIR LIQUIDE
Centre de Technologies et d'Expertises.
75 Quai D'orsay
75321 Paris
Cedex 07 France

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16. Abstract

Acoustic emission testing was studied to improve the safety, reliability and inspection efficiency of compressed gas tubes and cylinders. Laboratory tests on cylinders into which well-defined flaws were introduced compared acoustic emission testing with the permanent expansion measurements for sensitivity to plastic instability and evaluated the acoustic emission behaviour of cylinders. Full scale tests of tubes mounted on trailers were undertaken to determine test procedures to detect and locate sources of discrete acoustic emission events. Cylinders tested in the laboratory were pressurized hydrostatically to failure and simultaneously monitored by acoustic emission and permanent expansion measured as a function of pressure. Trailer tubes were tested hydrostatically and monitored using acoustic emission. Two acoustic emission testing options are advanced. Both offer enhancements over current procedures and economic advantages accrue to the operators of tube trailers in the case of both options. In the first option, the hydrostatic test is retained and acoustic emission testing is used at an overpressure of 5/3 of the service pressure in lieu of the water jacket. In the second option, tubes and cylinders are pressurized using the gas they normally transport as the pressurization fluid and monitored using acoustic emission at an overpressure of 110% to 115% of the service pressure. Any defects detected by acoustic emission would be subjected to ultrasonic and visual examination for confirmation and sizing, an additional inspection requirement at present. Rather than use fracture mechanics-based retirement criteria, it is proposed that crack-like defects that cannot be ground out leaving sufficient wall thickness to meet Compressed Gas Association (CGA) requirements be eliminated and that wall thinning must meet similar CGA requirements. Reliability enhancements from the use of acoustic emission are sufficiently advantageous that they should be implemented immediately.

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16. Résumé

La méthode de vérification des tubes et bouteilles de gaz sous pression, par émission acoustique, a été étudiée pour améliorer la sécurité et la fiabilité de ces fabrications ainsi que l'efficacité de leur inspection. Cette méthode a été utilisée en laboratoire sur des bouteilles comportant des défauts dont la nature est bien connue. Les essais en laboratoire ont visé à comparer cette méthode à celle des épreuves hydrauliques (mesure de la dilatation permanente), afin de déterminer laquelle est la plus sensible à l'instabilité plastique. Ils ont également servi à vérifier le comportement acoustique des bouteilles sous pression. Des essais exhaustifs sur des tubes montés sur semi-remorques ont été faits dans le but d'élaborer les procédures permettant de déceler et de focaliser les sources d'émissions acoustiques discontinues. En laboratoire, les bouteilles ont été soumises à des pressions hydrostatiques poussées au point de rupture, pendant que les émissions acoustiques et les dilatations permanentes étaient mesurées en fonction des pressions exercées. Des tubes montés sur semi-remorques ont été soumis à des épreuves hydrostatiques et contrôlés par la méthode des émissions acoustiques. La recherche a mis en évidence deux procédés de contrôle par émission acoustique, présentant des améliorations par rapport aux méthodes courantes, procédés permettant d'être intéressnts sur le plan économique pour l'exploitant dans le cas des tubes montés sur semi-remorques. Dans le premier procédé, il peut recourir aux épreuves hydrauliques et remplacer le procédé de pression extérieure (chemise d'eau) par celui de l'émission acoustique à une pression égale aux 5/3 de la pression de calcul. Dans le second procédé, les tubes et les bouteilles sont mis sous pression avec leur propre cargaison et les résultats observés par émission acoustique à une pression de l'ordre de 1,10 à 1,15 fois la pression de calcul. Un défaut mis en évidence par émission acoustique serait soumis à un examen visuel et par ultrasons dans le but de confirmer l'existence du défaut et de le dimensionner, contrôles qui ne sont pas requis pour le moment. Il est proposé que les critères de rejet fondés sur la mécanique de la rupture soient retirés et remplacés par le critère empirique élaboré par la Compressed Gas Association. Selon cette dernière, il ne faut tolérer aucun défaut de fissuration dont l'élimination par meulage amincirait la paroi au point de ne plus satisfaire aux exigences. Les améliorations apportées par le procédé d'émission acoustique à la sécurité des bouteilles de gaz sous pression sont telles que celui-ci devrait être adopté sans délai.

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SUMMARY

Acoustic emission testing was studied to improve the safety, reliability and inspection efficiency of compressed gas tubes and cylinders. Testing consisted of laboratory tests on cylinders into which well defined flaws were introduced and tested under well controlled laboratory conditions and full scale tests on tube trailers. The laboratory tests compared acoustic emission testing with the permanent expansion measurements for sensitivity to plastic instability and evaluated the acoustic emission behavior of cylinders. Full scale tests of tubes mounted on trailers were undertaken to determine test procedures to detect and locate sources of discrete acoustic emission events. Flaws generated for the tests were machined cuts, embrittled weld beads and fatigue cracks developed through pressure cycling. A cylinder was tested without any known flaw.

Cylinders tested in the laboratory were pressurized hydrostatically to failure and simultaneously monitored by acoustic emission. Permanent expansion was measured as a function of pressure. Trailer tubes were tested hydrostatically and monitored using acoustic emission. Acoustic emission behavior ranged from indications below the service pressure in freshly created flaws to indications which appeared only a few hundred psi before fracture. Early indications were followed by a dormant period until a sufficiently high load was reached where propagation and emission occurred continuously to failure. Cycling during the dormant period produced emissions on loading and unloading. Oxidation associated with wall thinning also provided copious acoustic emission. Five of the cylinders tested would have been rejected by hydrotest. Five of the cylinders would have been rejected by acoustic emission at an overpressure of 115% and nine at an overpressure of 5/3 of the service pressure. Among the latter nine, three would not have been detected by hydrotest but acoustic emission tests revealed they would have experienced crack extension due to the test itself. Thus, in the case of hydrostatic tests, use of acoustic emission is strongly indicated to detect any crack extension introduced by the test. Permanent expansion was not effective in revealing crack-like defects in these cylinders. Thus, there are two acoustic emission testing options. Both offer enhancements over current procedures. The option adopted by the operator would depend on his maintenance procedures and policies.

The water jacket has been shown to be insensitive to potentially dangerous flaws and serves little purpose. Economic advantages accrue to the operators of tube trailers in the case of both options. In the first option, the hydrostatic test is retained and acoustic emission testing is used in lieu of the water jacket. There are other economies since several tubes can be tested simultaneously and, due to the higher sensitivity for small flaws at the higher test pressure and crack retardation that occurs at the higher test pressure, the retest interval can be extended to ten years. In the second option, tubes and cylinders are pressurized using the gas they normally transport as the pressurization fluid and monitored using acoustic emission. Pressurization would be carried out to the highest value deemed safe and reasonable from test practicalities, and is of the order of 110% to 115% of the service pressure.

Any defects detected by acoustic emission would be subjected to ultrasonic and visual examination for confirmation and sizing, an additional inspection requirement not required at present. This offers both enhanced safety and economies to the operator of the vessels and to the public. While crack-like defects should be eliminated, it has been proposed that cracks up to 20% of the wall thickness could be tolerated. However, due to the rapidity with which an environmental assist can induce propagation, removal is always the most prudent course of action. An acceptable approach would be to retain the experience-based criteria set down by the CGA and to not accept any crack-like flaw that cannot be ground out leaving sufficient wall thickness to meet CGA requirements. This criterion could apply to both testing options described above.

Reliability enhancements from the use of acoustic emission are sufficiently advantageous that they should be implemented immediately.

SOMMAIRE

La méthode de vérification des tubes et bouteilles de gaz sous pression, par émission acoustique, a été étudiée pour améliorer la sécurité et la fiabilité de ces fabrications ainsi que l'efficacité de leur inspection. Cette méthode a été utilisée en laboratoire sur des bouteilles sous pression comportant des défauts dont la nature est bien connue. Les essais en laboratoire ont visé à comparer la méthode par émission acoustique à celle des épreuves hydrauliques (mesurage de la dilatation permanente) afin de déterminer laquelle est la plus sensible à l'instabilité plastique. Ils ont également servi à vérifier le comportement acoustique des bouteilles sous pression. Des essais exhaustifs sur des tubes montés sur semi-remorques ont été faits dans le but d'élaborer les procédures permettant de déceler et de localiser les sources d'émissions acoustiques discontinues. Quant aux défauts introduits exprès dans les fabrications soumises à ce contrôle, il s'agissait de coupures faites à la machine-outil, de soudures fragilisées et des fissures de fatigue obtenues par une mise sous pression cyclique. Un appareil ne comportant aucun défaut connu a servi de témoin.

En laboratoire, les bouteilles ont été soumises à des pressions hydrostatiques poussées au point de rupture, pendant que les émissions acoustiques et les dilatations permanentes étaient mesurées en fonction des pressions exercées. Des tubes montés sur semi-remorques ont été soumis à des épreuves hydrostatiques et contrôlés par la méthode des émissions acoustiques. Des informations acoustiques ont été obtenues dans un intervalle compris entre des pressions inférieures à la pression de calcul, dans le cas des défauts récemment introduits, et des pressions inférieures de quelque dizaines de kilograms par centimètre carré à la pression de rupture. Les premiers signaux acoustiques enregistrés ont été suivis par une période de latence qui s'est prolongée jusqu'au moment où une pression suffisamment élevée a induit une propagation des défauts et des émissions acoustiques qui n'ont cessé qu'à la rupture. Les alternances de pression durant la période de latence ont produit des émissions acoustiques, en charge comme en décharge. La corrosion accompagnant l'amincissement des parois a, elle aussi, été à l'origine d'une information acoustique abondante. L'examen par émission acoustique aurait rejeté comme inaptes au service cinq des bouteilles soumises à la pression de 1,15 fois leur pression de calcul, et neuf autres à une pression égale aux 5/3 de leur pression de calcul. Parmi ces neuf dernières, trois auraient pu échapper aux épreuves hydrauliques alors que la méthode acoustique a montré qu'elles comportaient des fissures qui se seraient propagées du fait de l'épreuve hydraulique elle-même. Ainsi, l'examen par émission acoustique est fortement préconisé dans le but de mettre en évidence toute propagation de fissures au cours d'une épreuve hydraulique. A l'égard de toutes ces bouteilles, les épreuves hydrauliques se sont révélées peu efficaces à mettre en évidence les défauts de fissuration. Deux procédés de contrôle par émission acoustique sont possibles, présentant des améliorations par rapport aux méthodes courantes. Le procédé que l'exploitant utilisera sera celui qui s'adapte le mieux au programme et aux procédures de maintenance que cet exploitant entend appliquer.

Le procédé de la chemise d'eau s'est révélé insensible à des défauts potentiellement dangereux et n'est donc que de peu d'utilité. Les deux procédés de contrôle acoustique promettent d'être intéressants pour l'exploitant dans le cas des tubes montés sur semi-remorques. Dans le premier procédé, il peut recourir aux épreuves hydrauliques et remplacer le procédé de la chemise d'eau par celui de l'émission acoustique. Ce procédé a l'avantage supplémentaire de permettre la mise à l'épreuve de plusieurs tubes en même temps et, étant donné que la sensibilité aux légers défauts est d'autant plus forte que la pression d'essai est élevée et que la propagation des fissures ralentit aux pressions élevées, d'autoriser des renouvellements d'épreuve par intervalles de 10 ans. Dans le second procédé, les tubes et les bouteilles sont mis sous pression avec leur propre cargaison et les résultats observés par émission acoustique. Les valeurs de pression mises en oeuvre pourront être choisies parmi les plus élevées jugées sécuritaires et techniquement praticables et qui sont d'habitude de l'ordre de 1,10 à 1,15 fois la pression de calcul.

Un défaut mis en évidence par émission acoustique serait soumis à un examen visuel et par ultrasons dans le but de confirmer l'existence du défaut et de le dimensionner, contrôles qui ne sont pas requis pour le moment. Ce contrôle secondaire profitera tant à l'exploitant qu'au public, en raison de la sécurité et des économies accrues qui en découleront. Alors que les défauts de fissuration doivent en principe être tous éliminés, il est proposé que les fissures intéressant jusqu'à 20 p. 100 de l'épaisseur de la paroi soient tolérées. Cela dit, il est toujours plus prudent de les éliminer, eu égard aux facteurs environnementaux susceptibles d'accélérer la propagation des fissures existantes. Une approche acceptable serait de tenir compte du critère empirique élaboré par la Compressed Gas Association. Selon cette dernière, il ne faut tolérer aucun défaut de fissuration dont l'élimination par meulage amincirait la paroi au point de ne plus satisfaire aux exigences. Un tel critère serait applicable aux deux procédés décrits plus haut.

Les améliorations apportées par le procédé d'émission acoustique à la sécurité des bouteilles sous pression sont telles que celui-ci devrait être adopté sans délai.

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ACOUSTIC EMISSION TESTING
OF
COMPRESSED GAS TUBE TRAILERS

1. INTRODUCTION

1.1. Project Requirements and Objectives

The transportation and storage of compressed gases is a widespread industrial practice. Gases most commonly transported are oxygen, hydrogen, helium, nitrogen, argon and air, while ethane, methane and natural gas as well as neon, krypton and xenon are transported less often. This project focussed on the improvement of safety, reliability and efficiency in the inspection of compressed gas containers using acoustic emission testing.

Currently, tubes must be inspected visually every two or three years and retested hydrostatically every five years. The current procedure is expensive, involves disassembly of the tubes, involves major vehicle downtime losses, and does not provide the maximum sensitivity to defects that current technology can provide. Several inspection procedure scenarios using acoustic emission would incur lower costs than present methods while providing enhanced safety.

Enhanced safety characteristics are:

- *the high sensitivity of acoustic emission testing*
- *acoustic emission's unique ability to locate flaws*
- *follow-up by other nondestructive inspection methods such as ultrasonic testing at flaw locations for full flaw characterization and evaluation.*

1.2. Report Organization

The first sections of this report describe the tubes and their materials of construction. This includes an overview of the general regulatory situation in which periodic testing must be carried out. Failure modes are outlined to provide an indication of the types of defects to be sought. The next sections review inspection and test methods in terms of their ability to efficiently and effectively detect the defects observed and anticipated in tubes. The report then proceeds to describe the experimental program undertaken to investigate the suitability of acoustic emission testing for inspection of tubes and the results obtained. Recommended testing procedures are presented in the the latter sections of the report.

2. REGULATORY OVERVIEW

2.1. Regulatory Bodies

The regulatory bodies in Canada and the U.S. responsible for material specifications of compressed gas containers are, respectively, Transport Canada and the Department of Transport (DOT). In practice there are no significant differences between Canadian and American regulations. Canadian standards are based on those set by the U.S. DOT. The responsibility in Canada was transferred to Transport Canada from the Canadian Transport Commission (CTC), on January 1, 1989.

Typically, seamless pressure vessels are manufactured by hot swaging the ends of pierced seamless tubes. These must be heat-treated in accordance with the appropriate specifications in effect at the time of manufacture. The specifications which apply are:

Specification CTC/DOT - 3A	Seamless Steel Cylinders
Specification CTC/DOT - 3AX	Seamless Steel Cylinders
Specification CTC/DOT - 3AA	Seamless Steel Cylinders
Specification CTC/DOT - 3AAX	Seamless Steel Cylinders
Specification DOT - 3T	Seamless Steel Cylinders

Standard specifications for carbon and alloy steel forgings for thin-walled pressure vessels are contained in designation A-372-81, under the jurisdiction of ASTM Committee A-1 on Steel, Stainless Steel and Related Alloys. This ASTM standard defines the materials, manufacture and testing of thin-walled pressure vessels. Included under this standard are also gas bottles, which are not classified as standard portable containers. Seamless pressure vessels for stationary gas storage are built to meet the ASME Boiler and Pressure Vessel Code, Section VIII, Division I and Code Case 1205 for storage of high pressure compressed gas.

2.2. Fabrication Specifications

Steel tubes used for the storage and transportation of industrial gases are fabricated in accordance with the applicable CTC and DOT specifications for each capacity and geometry. These specifications require that tubes be of seamless construction with integrally formed heads concave to pressure at both ends. The inside head shape must be hemispherical or ellipsoidal in which the major axis is two times the minor axis or a dished shape falling within those two limits. The formed tube is then machined for openings, heat-treated and pressure tested.

There are two types of closure used to seal the end of the tube. A spun tube, permitted for 3AX and 3AAX tubes, is one in which the end closure is welded by the spinning process. A plugged tube, permitted in specification 3AX, 3AAX and 3T tubes, is one in which the end closure is effected by a plug.

Regarding the minimum wall thickness of the tubes, CTC/DOT-3AX and 3AAX specifications require that the wall stress for tubes with service pressures less than 900 psi must not exceed 24,000 psi. In this case the minimum wall thickness for any tube over 127mm outside diameter will be 0.1" (2.54 mm). Minimum wall thicknesses are calculated using the Bach-Clavarino formula for wall stress (DOT specifications 178.37-16 and 178.37-17) (1). For 3AAX tubes with service pressures of 6.2 MPa or more the minimum wall thickness must be such that the wall stress at the minimum specified test pressure does not exceed the lower of 67% of the minimum tensile strength of the steel or 70,000 psi (483 MPa). The tensile strength is determined by a physical test specified by the DOT to whose results the Bach-Clavarino formula is applied.

Additional conditions are specified by the CTC and DOT for 3AX and 3AAX seamless tubes with water capacities of more than 453.6 KG and service pressures of at least 3.45 MPa. These specifications require that the tube must be horizontally supported at its two ends and uniformly loaded over its entire length. This load is the weight per unit length of the straight cylindrical portion filled with water and compressed to the specified test pressure. The sum of twice the maximum tensile strength in the bottom fibers due to bending plus the longitudinal stress due to hydrostatic test cannot exceed 80 percent of the minimum yield strength of the steel at this maximum stress. Wall thickness must be increased when necessary to meet this requirement. DOT specifications for 3T tubes (not covered in CTC standards and Regulations) require that the minimum wall thickness for this tube be such that the wall stress at the minimum specified test pressure not exceed the lower of 67 percent of the minimum tensile strength as determined by physical tests or a wall stress of 90,500 (624 MPa) psi. The minimum wall thickness for any tube may not be less than 0.225 in. (5.71 mm). The wall stress is calculated using the Bach-Clavarino formula. The additional conditions requiring the horizontal supporting of the tube at its ends and the uniform loading over the entire length are the same as for seamless tubes 3AX and 3AAX.

In summary, the minimum design wall thickness for 3AX or 3AAX tubes shall be the maximum value of the following:

a. the thickness based on Bach-Clavarino formula, and the assumptions of horizontally supported ends with a maximum wall stress not exceeding 380 MPa, or
b. a thickness equal to 0.225 in.(5.7 mm)

2.3. Chemical Composition and Heat Treatment

3AX seamless tubes are generally fabricated from carbon manganese or intermediate manganese steels [1]. Steel used for the fabrication of 3AX tubes must be fabricated by the open-hearth, basic oxygen, or electric furnace process. CTC 78.36-5 and DOT 178.36-5 specifications require that the steel used in fabrication be of uniform quality. The heat treatment as prescribed by DOT/CTC specifications 178.36-11 and 78.36-11 respectively must be uniformly and properly done prior to tests in order to relieve the completed tubes from fabrication-induced stresses, to provide uniform metal properties and to improve the yield strength of the materials.

Steels used for the fabrication of 3AAX tubes must also be fabricated of open-hearth, basic oxygen or electric furnace steels of uniform quality as required by specifications 78.37-5 (CTC) and 178.37-5 (DOT). Usually, these low-alloy steels include elements such as chromium, molybdenum and nickel [2]. Generally, Non-Standard Grade 4130X steels are used for 3AAX tubes, but any one of grade steels NE-8630, 9115, 9125, carbon-boron steel, and intermediate manganese steels can be used. According to specifications 78.37-6(b) (CTC) and 178.37-5(b) (DOT), when a carbon-boron steel is used, a hardenability test must be performed on the first and last ingot of each heat of steel.

Specifications 78.37-11 (CTC) and 178.37-11(5) (DOT) require that the completed tubes be uniformly and properly heat treated prior to tests. Heat treatment must be done in accordance with DOT sub-paragraph 178.37-11(5) which requires that non-standard grade 4130 X steel may be normalized at a temperature of 1650 degrees F. (899 degrees C.) instead of being quenched. Tubes so normalized need not be tempered.

For 3T tubes, DOT specification 178.45-5 requires the use of steel of uniform quality processed only by open-hearth, basic oxygen or electric furnace. The United States Steel Company fabricates these tubes from ASTM-A372 class V Type E quenched and tempered steel [3] which corresponds to AISI 4145 low alloy steel.

The heat treatment of 3T tubes is prescribed in DOT specification 3T. Sub-paragraph 178.45-8(a)(1), requires that the steel temperature on quenching cannot be in excess of 954 degrees C. Sub-paragraph 178.45-8(a)(2) states that after quenching each tube must be reheated to a temperature not less than 565 deg. C. Each tube must then be cooled under circumstances recommended for the steel.

The microstructure which results from quenching and tempering a low alloy steel is usually a tempered martensite or tempered bainite. Martensite forms throughout thin sections and an exterior skin on thick sections. Tempered bainite forms beneath the skin.

2.4. Mechanical Properties and Fracture Toughness

Mechanical tests on 3AX tubes must be carried out after final heat treatment in accordance with DOT/CTC specifications 178.36-15 and 178.36-16. Acceptable results from these mechanical tests must satisfy at least one of the requirements of paragraphs 178.36-17.

Specification 178.36-15 specifies that for each lot of 200 tubes or less a flattening test must be performed on a single tube chosen at random from the lot. However, for lots of 30 tubes or less, the same paragraph specifies that physical and flattening tests would be made on a ring at least 8 inches long, cut from each tube and subjected to the same heat treatment as a finished tube.

The physical test specified is the complete determination of mechanical properties, i.e., yield strength, tensile strength, elongation and reduction areas of the material.

DOT/CTC regulations specify that the material used for the fabrication of 3AX tubes must have the minimum tensile strength specified in paragraph 178.36-17, that satisfies the requirements of paragraph 178.36-10. Values determined for an intermediate manganese steel used by United States Steel Company are given below [4]:

Minumum Tensile Strength:	552 MPa
Minimum Yield Strength:	379 MPa
Maximum Elongation in 2 in.:	20 %

For 3AAX tubes the steel used for fabrication must be an alloy steel of uniform quality conforming to one of the chemical compositions specified in paragraph 178.37-5. The mechanical properties of the steel used must be determined in agreement with paragraphs 178.37-15 and 178.37-16, consistent with the requirements of paragraphs 178.37-10 and 178.37-17. A relation can be established between the geometry of the tube, tensile properties of the material and the maximum test pressure prescribed for the water jacket test.

Paragraph 178.37-10 states that the minimum wall thickness of 3AAX tubes with service pressures over 6.2 MPa must be of a thickness that the wall stress at the minimum specified test pressure does not exceed two-thirds the minimum tensile strength of the steel. The minimum tensile strength must be determined by the physical tests specified. Wall stress cannot exceed 483 MPa.

The typical grade of steel used by US Steel Company in the fabrication of 3AAX tubes is non-standard grade AISI 4130X. Values for the tensile properties of this high-strength low alloy steel are listed below [1]:

Tensile strength in psi:	724 MPa
Yield strength in psi:	483 MPa
Elongation in 50.8mm:	20 %

The steel used for fabrication of DOT-3T tubes is specified in paragraph 178.45-5 and its chemical composition corresponds to the grade known as ASTM-A372, Class 5, Type E and also to grade AISI 4145. Mechanical properties of this high strength low alloy steel must be determined in accord with paragraph 178.45-13 and 178.45-14 to satisfy the requirement of 178.45-7 and 178.45-15.

Typical values for tensile properties of this high strength low alloy steel are listed below [5].

Tensile strength in psi:	931 MPa - 1,069 MPa
Yield strength in psi:	759 MPa - 966 MPa
Elongation in 2 in. :	22 %

In subparagraph 178.45-15 (a)-(1) (DOT-3T) it is stated that the tensile strength may not exceed 931 MPa. Subparagraph 178.45-15 (a)-(2) specifies that the elongation must be at least 16% for a 50.4mm gage length.

Paragraph 178.45-7 (a) (DOT-3T) requires that the minimum wall thickness be such that the wall stress at the minimum specified test pressure does not exceed 67 percent of the minimum tensile strength of the steel. The minimum tensile strength of the steel is determined by the physical tests specified. A wall stress of more than 624 MPa is not permitted. Charpy specimens of the steel must be prepared and tested in accord with paragraph 178.45-13 (DOT-3T).

The test results must conform to the requirements specified in paragraphs 178.45-14 and 178.45-15. When the test results do not conform to the requirements specified, the tubes may be reheated and the tests repeated.

2.5. Modes of Transportation and Packaging

Within CTC and DOT specifications a large variety of tube trailer and stationary storage configurations are possible. On vehicles, the tubes are mounted on skids or frames. Weight limitations for these vehicles are based on DOT gross vehicle weight restrictions (36288 Kg. for tractor trailers). Specification 173.301(K) states that 3AX, 3AAX and 3T tubes can only be transported horizontally, with valves and safety devices as follows:

1. each tube must be fixed at one end of the vehicle with provision for thermal expansion at the opposite end attachment
2. the valve and pressure relief device protective structure must be sufficiently strong to withstand a force equal to twice the weight involved with a safety factor of four, based on the ultimate strength of the material used; and
3. each discharge path for a pressure relief device on a tube containing a flammable gas must be directed upward and must be unobstructed.

2.6. Service Pressure and Filling Limits

CTC specifications require that the tube pressure at 21 C not exceed the service pressure for which the container is marked or designated, except as provided in CTC specification 73.302(c) and DOT specification 173.302(c).

Safety regulations focus on the following areas:

a. the type of tubes in which each gas may be shipped
b. the charging of the tubes as to amount of gas and filling conditions
c. the requirements for marking and labeling of tubes for transportation
d. the requirements for qualifying, maintaining and requalifying tubes
e. the conditions under which a tube may be transported.

CTC specification 73.302(a)(3) authorizes 3AX and 3AAX tubes to be used only for transportation of the following nonliquefied gases:

air, argon, helium, hydrogen, nitrogen and oxygen.

DOT specification 173.302(a)(3) authorizes the use of 3AX, 3AAX and 3T tubes only for the following nonliquefied gases:

air, argon, boron triflouride, carbon monoxide, ethane, ethylene, helium, hydrogen, methane, neon, nitrogen and oxygen (3T tubes cannot carry hydrogen or natural gas).

Methane gas is considered a non-liquefied gas which has a minimum purity of 98.0% methane and which is commercially free of corroding components.

Special filling limits are permitted by DOT and CTC for 3AX, 3AAX, and 3T (DOT only) tubes. These tubes may be charged with compressed gases (other than liquefied, dissolved, poisonous or flammable gases) to a pressure 10% in excess of their marked service pressure, provided that:

1. such tubes are equipped with frangible disc safety relief devices (without fusible metal backing) having a bursting pressure not exceeding the minimum prescribed test pressure.
2. the elastic expansion has been determined at the time of the last test or retest by the water jacket method
3. an adequate method has been used to examine the tube inside and outside at specified testing intervals and the results show no excessive corrosion, pitting or dangerous defects in the tube.
4. that either the average wall stress or the maximum wall stress shall not exceed the wall stress limitation in DOT sub-paragraph 173.302(c) (3).

2.7. Retesting and Reinspection Intervals and Requirements

All pressure containers, pressure vessels, trailers, skids and storage packs become due for a periodic retest five years from the original test date. The retest must include a visual internal and external examination and a test by interior hydrostatic pressure in a water jacket or alternate apparatus to determine the expansion of the tube. The test apparatus must be CTC/DOT approved as to type and operation by the CTC/DOT.

Under DOT/CTC guidelines, tubes must be tested at the retest pressures and intervals stated in Table 1 below: [5]

TABLE 1: Minimum Retest Pressure and Retest Period [1]

Cylinder Specifications	Minimum Retest Pressure	Retest Period
CTC-3AX, 3AAX	5/3 x service pressure	5 years
DOT-3T *	5/3 x service pressure	5 years

* 3T tubes are not included in CTC specifications.

3. TUBE FAILURE

3.1. Failure Modes and Causes

Medium and high-strength alloy steels are used in tube construction to maximize operational efficiency by maximizing payload while minimizing weight. Initial crack-like defects are unavoidable during fabrication. These defects are subject to degradation mechanisms which initiate the failure process. Deterioration of strength is related to:

- the relation between defect size and structural resistance, and
- the combined effect over time of defect propagation and applied load on defect size.

Failure modes nay be instantaneous or time-dependent. Instantaneous failure is an instantaneous collapse of the margin between strength and stress. Time-dependent failures involve a gradual reduction of the margin between strength and stress over a given period of time. The form of such time-dependent failure depends on the failure mode itself [6].

In time-dependent failures, the deterioration of a component can often be detected before failure occurs. The duration of the warning period involved is a function of the sensitivity of the detection apparatus and the magnitude of the failure propagation rate. This type of inherent failure mechanism can usually be avoided if an imminent failure is detected and appropriate actions taken.

In general the normal operation of compressed gas tubes proceeds safely as long as operating conditions are adequately monitored and controlled. The operating environment, however, subjects the tube to high pressure operation, a pressure cycling regime and an aggressive environment. Accidental fractures have occurred in both Europe and North America in containers holding hydrogen, natural gas, carbon monoxide and its mixtures, carbon dioxide and even compressed air [7].

Three types of corrosion and environment-assisted cracking are of concern because with sufficient circumstances they can cause crack propagation, and ultimately result in failure [10]. These processes are the following:

1. General Corrosion, including pitting (PC)
2. Sulfide Stress Cracking (SCC) and
3. Hydrogen Embrittlement (HE).

General corrosion can be either internal or external. External corrosion is common to all types of steel containers. Surface roughness or small discontinuities on the inner tube wall can accelerate the internal corrosion phenomenon.

Sulfide stress cracking and hydrogen embrittlement are forms of environment-assisted cracking; i.e., crack growth via interaction between one or more harmful chemical species and stressed steel at the crack tip [5]. Specifically, sulfide stress cracking is defined as brittle fracture by cracking under the combination of tensile stress and corrosion due to the presence of water and hydrogen sulfide. This mode of failure is characteristic of high strength steels (yield strength above 552 MPa). Hydrogen embrittlement is defined as a metal's loss of ductility such that its tensile strength is greatly reduced caused by interaction between hydrogen gas and the metal surface. This is a form of localized embrittlement of the material at the tip of the crack, and occurs in some steels when freshly created fracture surfaces are exposed to gaseous hydrogen under pressure [7]. Hydrogen also reduces the minimum or threshold stress intensity factor (K_{ISCC}) of the metal for crack growth under static loading. This results in a significant increase in the fatigue crack growth rates of some metals.

While loss of ductility is common to both high and low strength steels, cracking failures occur only in high strength steels; i.e., steels which have a yield strength above 966 MPa. Experience has determined that low alloy steel chromium-molybdenum steel tubes are especially susceptible to hydrogen embrittlement. 3T tubes made with AISI 4145 and ASTM-372, Class 5 ,Type E steels having a yield strength of 869.4 MPa to 1055.7 MPa and tensile strength of 145 to 164 are considered very susceptible to hydrogen embrittlement [11]. Under the influence of hydrogen sulfide, environmentally-assisted cracking will occur at applied stresses as low as 138 MPa. Other chromium-molybdenum tubes heat treated to a yield strength of 483 MPa to 786 MPa and a tensile strength of 724 MPa to 910 MPa are considered moderately susceptible to HE. This type of steel is used for the manufacture of 3AAX tubes [11]. The tube is subject while in use to aging and environmental influences such as ambient temperature, which tend to increase the hardness of the metal. It has been determined that this in turn makes the tube more susceptible to HE [7]. Variations in chemical composition and microstructure can also increase the susceptibility of the tube to hydrogen embrittlement if they increase the hardness of the metal.

3.2. Failure Analysis

Accident occurences in the last twenty years involving road transportation of compressed gas containers have been investigated in depth. Metallurgical analyses of failed tubes have determined that the progression to failure is not the result of a single mechanism. Incident studies of tube failures in different countries established the following as causes of failure:

England: stress corrosion due to moisture and sulfur impurities and pressure-induced hydrogen environment cracking in a tube made from a chromium-molybdenum steel [8].

Italy: failure of low alloy chromium-molybdenum steel carrying carbon monoxide attributed to stress corrosion attack by hydrogen sulfide [9].

U.S.A.: failure of a large seamless steel pressure tube attributed to environmentally assisted cracking due to high concentrations of hydrogen sulfide and sulfur compounds [5].
natural gas: internal corrosion due to chemical reaction of the acid solution formed by the dissolution of carbon dioxide in the water vapour contained in the gas [5].

In the United Kingdom none of the containers failed catastrophically and those that did fail were hydrogen tube trailers.

These failures were found to have a number of characteristics in common:

- the fracture initiated on the inner surface in the position where the thin-walled parallel section meets the thicker knuckle region
- in most of the failures, the fractures initiated at inner wall surface defects about 0.1 mm deep on the inner wall and had propagated in a brittle manner by a mixed intergranular/transgranular mode
- the cracks tended to follow the distribution of the inclusions which are mainly manganese sulfide
- the metallurgical structure in the vicinity of the cracks was tempered
- the quality of the containers met required specifications
- there was no evidence of any manufacturing defects or defective material
- NDT tests showed that the material quality in the region of the failure was equal to material quality in the parallel wall section. Toughness was at the expected level for quenched and tempered steels at that strength level.

- the absence of gross defects, the good quality of the steel, and the indications on the fracture surface establish that the fractures grew in service and were not manufacturing faults.

The overall conclusion of these metallurgical investigations is that the failures were not the result of a single degradation mechanism but were rather the result of environmentally assisted cracking defined as "crack growth via interaction between one or more harmful chemical species such as H_2, H_2S, CO or CO_2+H_2, etc., and stressed steel at the crack tip" [5].

4. INSPECTION

4.1. Methods, Standards, Codes and Regulations

At the time of manufacture a hydrostatic proof test must be performed. After this test the cylindrical section of each seamless vessel must be examined using the ultrasonic angle beam technique in accordance with ASTM Standard A-388. DoT Specification 178.45-82 requires that the equipment must be calibrated to detect a notch equal to five percent of the design minimum wall thickness. The following ASTM Standards also are applicable:

E 114-82	Recommended Practice for Ultrasonic Pulse-Echo Straight-Beam Testing by the Contact Method
E 317-82	Practice for Evaluating Performance Characteristics of Ultrasonic Pulse-Echo Testing Systems Without the Use of Electronic Measurement Instruments
E 500-82	Definition of Terms Relating to Ultrasonic Testing

DoT Specification 178.45-12 requires that a cylinder be rejected if a discontinuity indication greater than that produced by the five percent notch is found, unless the discontinuity is repaired within the requirements of this specification. DoT Specification 178.45-12 applies only to the manufacturing level. During requalification (rehabilitation) of tube trailers the following ASTM Standards apply:

E 213-83	Practice for Ultrasonic Inspection of Metal Pipe and Tubing
E 797-81	Ultrasonic Pulse-Echo Contact Method, Measuring Thickness by Manual
E 1002-84	Leak Using Ultrasonics

In accordance with DoT Specification 178.37-11(6) 3AA and 3AAX cylinders must be submitted to a magnetic test after heat treatment to detect the presence of quenching cracks. Cracked cylinders should be rejected. Further, paragraph (8) of the same spec. requires an obligatory inspection by magnetic particle, dye penetrant or ultrasonic method to test for the presence of quenching cracks if the metal was quenched with a liquid producing a cooling rate in excess of 80 percent of the cooling rate of water. 3AA cylinders found to have cracks must be rejected and cannot be requalified. 3AAX cylinders must have the cracks removed to sound metal and be subsequently examined to assure that the defect has been removed and that thickness remains within required limits.

Experience has shown that failure under an environmental assist can propagate rapidly and, in certain instances, in periods less than mandated inspection intervals. While pre-service tests must check for manufacturing defects and verify the initial fitness for service, periodic in-service inspections must check for incipient, low probability defects that may propagate to failure in short times.

The hydrostatic test with volumetric expansion provides and overall evaluation of the vessel condition but is insensitive to small crack-like defects. Other, more sensitive NDT methods such as ultrasonics require 100% volumetric coverage of the vessel and thus are costly and impractical. Acoustic emission provides comparable sensitivity without the need to traverse the entire vessel with the search probe.

4.2. Hydrostatic Test

Proof testing is an effective method for screening out components containing intolerable initial defects. It is common practice to perform proof tests on pressure vessels prior to service in order to ensure their safety and reliability in service. Pre-service and in-service overpressure testing is well established as a means of establishing fitness for service and to avoid disruptive failure for a definite period of time [9,10].

Containers for compressed gas transport are subjected to proof testing by hydrotesting before they enter service and at five-year intervals thereafter. Each tube must be tested at an internal pressure of at least 5/3 of service pressure either by the water jacket method or another acceptable method. This test is also done to ensure complete volumetric expansion and to measure the permanent volumetric expansion. If the permanent expansion in the test exceeds ten percent of the total volumetric expansion, or there is evidence of any leaks, internal or external corrosion, denting, bulging or any other significant sign of weakness, then the regulations recommend rejection or removal from service. A tube must also be condemned if the elastic expansion exceeds the marked rejection elastic expansion (REE) measured in cubic centimeters. The REE for a cylinder is 1.05 times its original elastic expansion prior to the next retest date [11,12]. It is recommended that the pressure be maintained for 30 seconds or more to insure complete expansion.

The hydrostatic test supplements fabrication control before operation. The validity of the test is based on testing for a limiting size of defect which does not fail even under pressure test conditions. Quantitative conclusions have been drawn on the implications of hydraulic proof testing to remanent crack size [13]. Pressure cycling can cause a defect to grow by fatigue or stress corrosion. By relating fracture toughness, stress levels and defect size, a limiting maximum size of defect can be calculated from which the extent of pressure cycling which would cause such defect growth could be predicted.

In idealized conditions it is assumed that all operational stresses are of lower magnitude than those during pressure testing. Operational stresses are taken to be of the same nature as those in the pressure test, and fracture toughness assumed to precisely define the failure mode. Also, the toughness is taken as constant during both pressure testing and service conditions. These assumptions are only likely in brittle materials. Conclusions for more ductile materials will be strongly influenced by ductile crack extension, deviation from plane-strain conditions, and wide variation in fracture toughness properties over temperature ranges and through time. As important indicators of safety and reliability, these factors must be taken into account.

4.3. Acoustic Emission Testing

Following a successful hydrostatic proof test, fracture mechanics enables establishment of the maximum flaw that exists in the component. However, although the test demonstrates that no flaw exceeds a limiting size, the actual size of any existing flaws are unknown. It would be desirable if the same proof test could be used to locate sub-critical defects and assess their size, thereby measuring any defect growth between tests and enhancing the applicability of test results to

subsequent operation. Acoustic emission is sensitive to such subcritical defects when they are active and potential sources of degradation.

Hydrotesting sometimes causes catastrophic failure. Although this is a rare event, economic penalties are severe. Acoustic emission systems can be used during inspection to provide information needed to avoid failure. Acoustic emission capabilities include the ability to monitor the progress of a hydrotest and generate an abort decision if flaw growth should occur. This capability offers the possibility of evaluating defect severity and determining the associated risk for a structure.

Acoustic emission also has the unique capabilities of being able to detect elementary fracture processes in real time and to assess the structural integrity of an entire structure rather than just a local area. Where a large surface area must be inspected, acoustic emission is considered the fastest, most sensitive and most efficient inspection method, primarily because it can be performed while the structure is in service.

In conventional testing methods, defect detection and evaluation of defect impact on the structure are separate functions. In acoustic emission testing, test results and expected structural behaviour are interrelated by the nature of the acoustic emission phenomenon which detects active defects. In some test procedures, cost savings are realized by on-site testing and elimination of disassembly requirements and the testing method can use the actual product as the pressurization fluid and the plant filling station pressurization system reducing contamination problems and testing costs.

5. TESTING PROGRAM

5.1. Test Program Scope and Objectives

The test program consisted of laboratory tests and tests carried out on tube trailers. Laboratory tests were added to the program after early Steering Committee deliberations. While initial tests of tubes showed that minute defects could be detected, it was evident that a substantial number of defects would not be observed during the course of normal inspection. It was deemed necessary to implement a series of tests on vessels into which well-defined flaws had been introduced and could be tested under well-controlled laboratory conditions.

While the objectives of the project were addressed to both tubes and cylinders, the laboratory tests were carried out on cylinders due their lower cost and better availability. Due to similarities in construction and materials, it is assumed that the results and conclusions obtained on the cylinders can be extrapolated with confidence to tubes. The objectives of the laboratory tests were to:

- effect a direct comparison of acoustic emission testing with the water jacket tests for sensitivity to plastic instability.
- to evaluate the acoustic emission behavior of cylinders
- to measure crack growth rates
- to measure crack retardation due to overstressing at the hydrostatic proof load.

Acoustic emission examination of compressed gas tubes mounted on trailers was undertaken to determine appropriate test procedures to detect and locate sources of discrete acoustic emission events.

5.2. Instrumentation

The Tektrend Acoustic Emission Source Detection and Location System provides a real time display of acoustically active sources and their relative severity. The system accepts inputs from up to 64 sensors, measures relative arrival times, calculates source coordinates, and displays source location and activity information in real time on a computer terminal and records pertinent information on a printer in the test vehicle. Two sensors were mounted on each tube for source detection and location. Display of the location of each AE event in relation to the position of the sensors and plots of event time history and correlations with external parameters (e.g. pressure) provide real time decision-making on the integrity of the tubes under test. Hardware and software signal discriminating capabilities identify and reject spurious noise due to EMI and other background effects. System specifications are shown in Table 2.

TABLE 2: Test System Specifications

Sensors:	AC-375l, Single Ended, 375kHz Resonant Frequency TSI-AE-.375, Single Ended, 375kHz Resonant Frequency
Filters:	250-500 kHz
Tektrend Preamplifier Gain:	60dB
Tektrend Amplifier:	Programmable 0-40dB
System Threshold:	0 to 2.55V Floating above R.M.S. or Fixed
Arrival Time Resolution:	32 Microsecond-62 Nanosecond Programmable
Parametric Inputs:	Pressure 0 to 34.5 MPa

5.3. Laboratory Test Specimens

Artificial flaws were introduced by machining cuts into the cylinders, fatiguing three cut cylinders and by producing local metallurgical changes to enhance initiation. A total of 17 cylinders of varying specifications and flaw types were tested. The three main types of flaws that were generated for the tests were machined cuts, weld beads and fatigue cracks developed through pressure cycling. Two types of machined cuts were milled into the wall, longitudinal and transverse. Nine longitudinal cuts were made in three depths 0.16cm, 0.3175cm and 0.477cm and each with three lengths, 5.08cm, 10.16cm and 15.24cm. Additionally, two more cylinders were cut perpendicular to the length with depths of 0.16cm and .3175cm.

Two cylinders were prepared with arc weld beads to generate flaws and control the initiation site. Weld beads of approximately four inches were laid down in three different locations along the long axis of the cylinder. Immediately after welding, the areas were quenched in water to embrittle the area.

Three additional cylinders were prepared in France by Air Liquide. In these cylinders, wall thinning was created by milling longitudinal cuts approximately .3175cm deep. At this point the cylinders were fatigued by hydrostatically pressurizing to the rated pressure of the cylinder. One cylinder was cycled 5800 times and one 9400 times. Using a crack opening displacement gage the progress of the generated flaw was monitored. A third cylinder was prepared the same way except, in this case, the flaw was maintained in a moist environment so as to induce visible corrosion of the flaw. A final cylinder was tested without any known flaw introduced either artificially or naturally. Table 3 summarizes the test series.

TABLE 3. Test Cylinders

Number	Flaw Type		Dimensions	No.	Flaw Type		Dimensions
1.	Artificial	Longitudinal Cut	5.08cm x 0.16cm	2.	Artificial	Longitudinal Cut	5.08 x.3175
3.	Artificial	Longitudinal Cut	5.08cm x .477cm	4.	Artificial	Longitudinal Cut	10.16x.157
5.	Artificial	Longitudinal Cut	10.16 x .3175	6.	Artificial	Longitudinal Cut	10.16 x .477
7.	Artificial	Longitudinal Cut	15.24 x .157	8.	Artificial	Longitudinal Cut	15.24 x .3175
9.	Artificial	Longitudinal Cut	15.24 x .477	10.	Artificial	Transverse Cut	.3175
11.	Artificial	Transverse Cut	.477	12.	Natural	Arc Strike	
13.	Natural	Arc Strike		14.	Natural	Crack (5400 cycles)	
15.	Natural	Crack (9400 cycles)		16.	Natural	Corroded Crack	
17.	No Flaw						

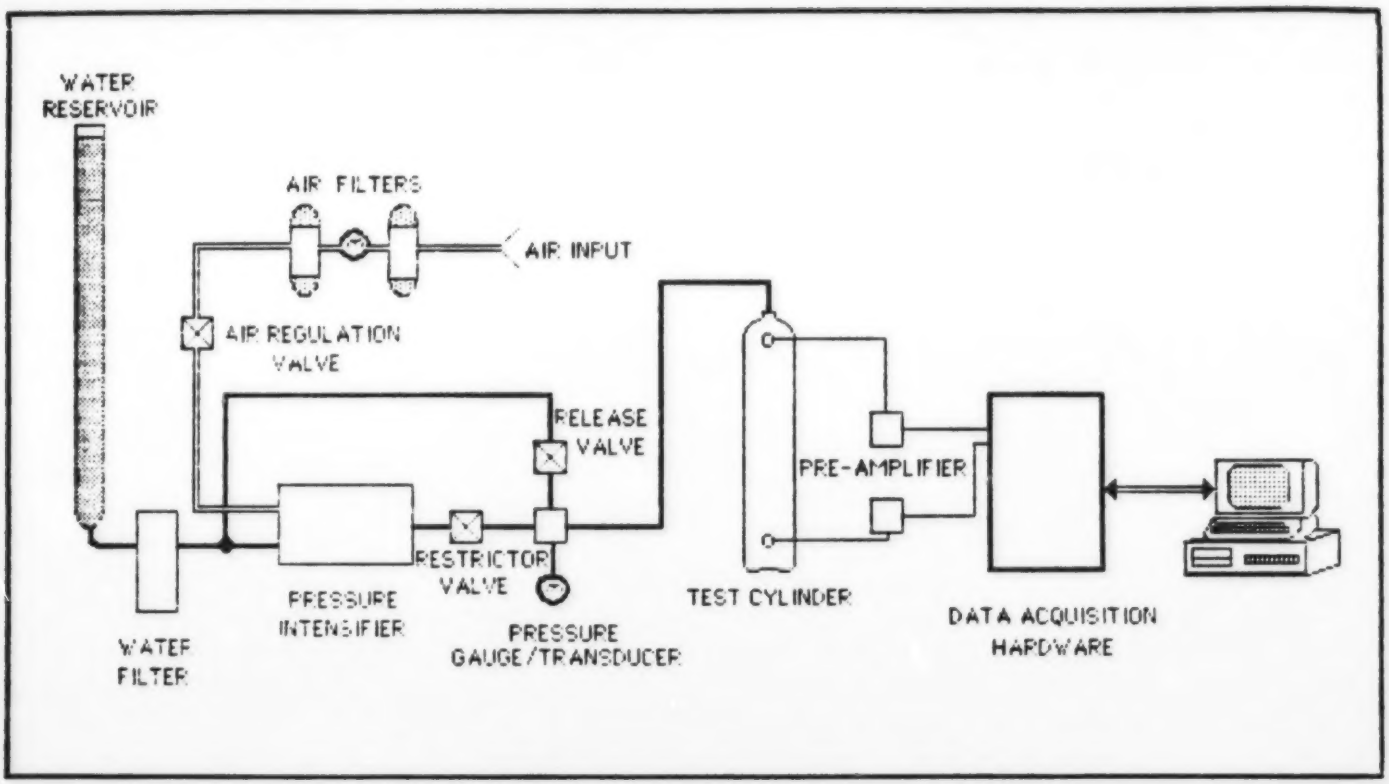
5.4. Laboratory Test Procedure

Laboratory tests were carried out on cylinders which were pressurized hydrostatically and simultaneously monitored by acoustic emission. The test set-up is shown in Figure 1. The weight of the cylinder empty and full was measured to determine the volume of the cylinder and the direct expansion method was used to determine expansion of the cylinder during hydrostatic testing (15). Hydrostatic pressure was applied using a Teledyne air-driven pressure intensifier. Two acoustic emission transducers were coupled to the cylinder under test at each end to detect and locate acoustic emission. Gains of 80 db and thresholds of 60mv floating above the rms of the signal were used. Acoustic emission events were recorded as a function of time, pressure and location.

The pressure was increased incrementally by cycling between zero and the following values until failure:

0 - 10.3 MPa 0 - 13.8 MPa 0 - 14.5 MPa 0 - 15.2 MPa
0 - 5.9 Mpa 0 - 17.25MPa 0 - 20.7 MPa 0 - 24.8 MPa
0 - 24.1 MPa, then in 3.5 MPa increments until failure.

This cycling back to zero permitted measurement of the expansion by the direct method for each incremental pressure level.



Compressed Gas Cylinder Test Configuration

Figure 1. Test Setup for Laboratory Tests

5.5. Tube Trailer Tests

The testing methodology is, in principle, the same as used for pressure vessels and tanks. The testing practice was made compatible with standard codes, regulations and recommended practices including:

ASTM Standards:

E 569	Standard Recommended Practice For Acoustic Emission Monitoring of Structures During Controlled Stimulation.
E 610	Standard Definition of Terms Relating to Acoustic Emission.
E 650	Standard Recommended Practice for Mounting Piezo-electric Acoustic Emission Contact Sensors.
E 750	Standard Practice for Measuring the Operating Characteristics of Acoustic Emission Instrumentation.

ASME Standards: Proposed Standard for Acoustic Emission Examination During Application of Pressure.

EWGAE Standards: Code for Acoustic Emission Examination: Location of Sources of Discrete Acoustic Events.

Acoustic emission monitoring during pneumatic overpressurization was carried out on the following trailers:

TABLE 4. Tube Trailer Tests

Trailer Number	Test Date	Pressurization Fluid	Number of Tubes Tested	Couplant Used
1	Feb 26, 1986	Nitrogen	5	Clear silicon Seal
2	Feb 27,28, 1986	Nitrogen	9	Clear Silicon Seal
3	Aug 25, 1986	Hydrogen	32	Hot Glue
4	Sep 10, 1986	Hydrogen	32	Hot Glue
5	Oct 8, 1986	Hydrogen	32	Hot Glue

Sensors were attached to the tubes using the couplants/fixants indicated in Table 4. Equipment and test parameters used for the tests are listed in Table 3. A pressure transducer was installed into the pressure line for continuous pressure monitoring and recording. Source location was calibrated prior to the start of each test. This was accomplished by introducing simulated AE signals into the tubes. The actual locations were compared with the resulting computed locations to determine locational accuracy. The locational accuracy of each array to a simulated source was within +/-5% of sensor spacing. The tubes were subjected to increasing pressure while monitored by acoustic emission.

5.6. Laboratory Tests

The observed burst pressure and the pressure at which acoustic emission is first observed (AE Pressure) are compared in Table 5. The overpressure (Ratio) at which emission first occurs in these artificial flaws ranges from 0.75 to 2.47 of the normal service pressure. Permanent volumetric expansion at the normal hydrotest pressure was less than 5% for each cylinder whose burst pressure.

Number	CTC/DOT Spec.	Service Pressure	Thickness	Defect Dimensions Length x Depth (cm)	Observed Burst Pressure	AE Pressure	Ratio
LONGITUDINAL FLAW							
1	3A	13.9 MPa	0.787	5.08 x 0.16	36.3 MPa	14.1 MPa	1.01
2	3A	13.9 MPa	0.721	5.08 x 0.3175	29.6 MPa	26.6 MPa	1.91
3	3A	12.4 MPa	0.772	5.08 x 0.477	20.8 MPa	13.8 MPa	1.11
4	3A	13.9 MPa	0.724	10.16 x 0.16	35.0 MPa		2.35
6	3A	13.9 MPa	0.813	10.16 x 0.477	20.7 MPa	20.4 MPa	1.47
7	3AA	13.9 MPa	0.602	15.24 x 0.16	34.6 MPa	34.4 MPa	2.47
8	3A	13.9 MPa	0.571	15.24 x 0.3175	19.9 MPa	18.2 MPa	1.31
9	3A	13.9 MPa	0.673	15.24 x 0.477	16.8 MPa	15.9 MPa	1.15
TRANSVERSE FLAW							
10	3A	13.9 MPa	---	0.3175cm	34.5 MPa	12.4 MPa	0.90
WELDS BEADS							
12	3A	13.9 MPa			41.3 MPa	39.3 MPa	2.83
13	3A	13.9 MPa			35.2 MPa	31.6 MPa	2.29
FATIGUED							
14		20.7 MPa			29.7 MPa	15.5 MPa	0.75
15		20.7 MPa			33.1 MPa	30.8 MPa	1.49
16		20.7 MPa			36.3 MPa	31.4 MPa	1.52

Figure 2 shows an emission versus time profile that contains the features observed in this series of tests. The results are taken from the third tube in Table 5, where several sites showed early emission which increased as failure progressed. The event history is shown in Figure 3 as a function of location and time. First emission was observed on the loading part of a -

cycle. During the next four cycles emission occurred on unloading and reloading between cycles and at low load levels. On the last two cycles, Kaiser effect extension was observed and, on the last cycle, unstable crack growth. This behavior was generally observed on all longitudinal cracks. It was absent in the transverse cracks of which Figure 4, for a 3.18cm deep cut, is an example and where the Kaiser effect prevails.

Introducing quenched weld beads successfully produced flaws that emitted early in the loading cycle. In the cylinder shown in Figure 5 emission first occurred at 2100 psi from the center flaw. A second flaw began emission at 26.2 MPa with a burst of two closely spaced emissions and a third flaw became active at 29.8 MPa. The evaluation of all three artificial flaws as well as a fourth indication at one end are shown in Figure 6.

Fatigued specimens varied in behavior. Figure 7 shows the results from one tube where emissions began early in the loading cycle at less than the service pressure. Flaws on two other similar tubes were more stable and required higher stress levels to propagate.

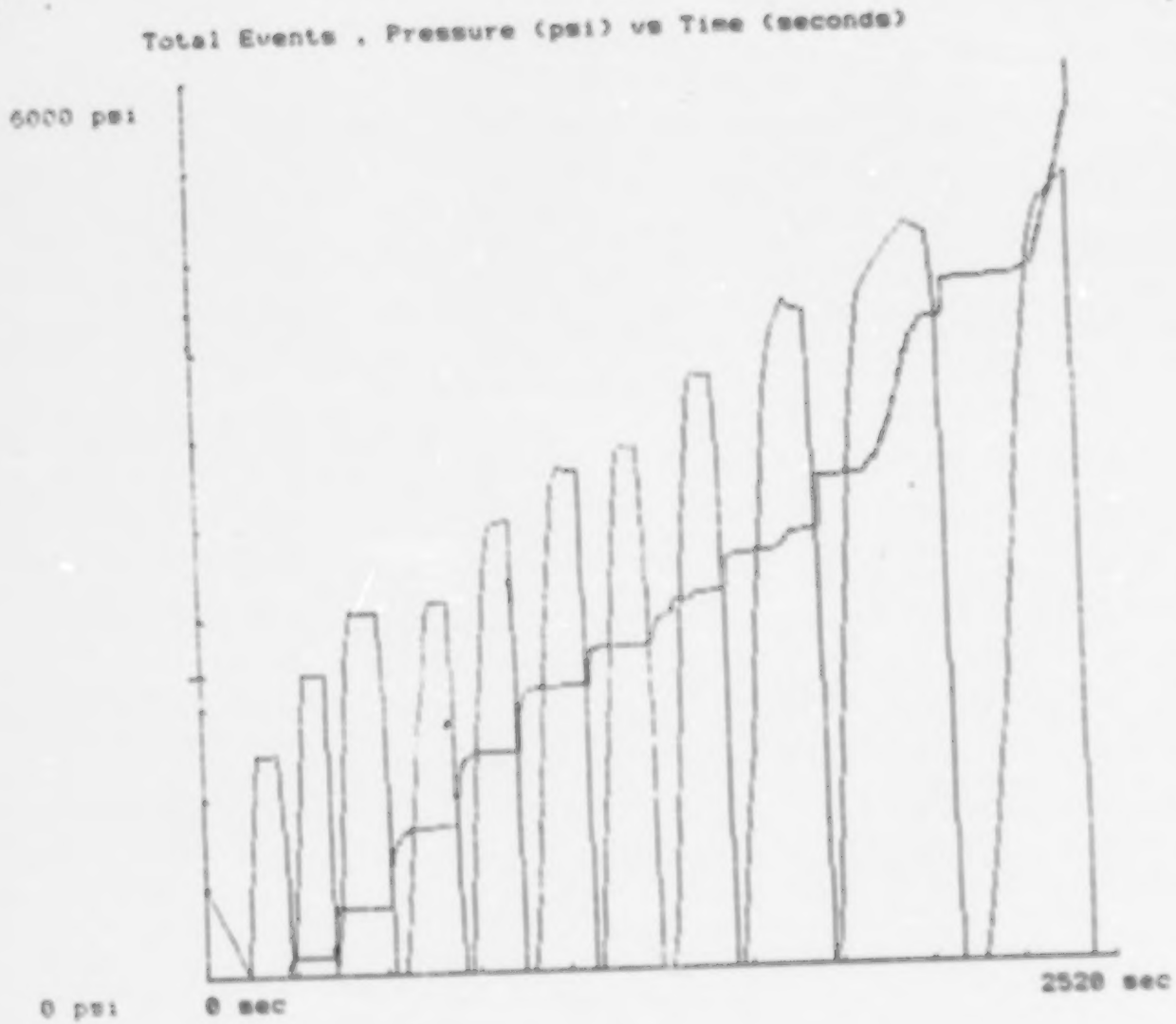
5.7. Tube Trailer Results

ASTM 569-82 classifies each acoustic emission source as a function of its criticality. Three grades of criticality have been identified for structural evaluation and assessment. For example, if an acoustic emission source does not continue to emit signals as pressure continues to increase, the source behaviour indicates a non-crack defect which is not active at higher stress levels. This is a Grade C source and does not influence structural integrity. A grade B source is more severe that Grade C, and should be taken into consideration during the subsequent testing of the structure. Grade A sources indicate critical severity and require immediate attention and further investigation.

One Grade A source and three Grade B sources were called during this series of tests on the five trailers. Follow-up inspection was carried out on the Grade B sources on a trailer tested in February 1986. Follow-up inspection was visual, ultrasonic and dye penetrant. Where rust was present, the area was cleaned and inspected visually. In one such area, a lamination was detected visually and confirmed by dye penetrant. It was shallow and determined to be acceptable. Other similar areas were inspected with penetrants and no defects were detected. Ultrasonic inspection was carried out at all locations and no indications were observed even at the visually observable lamination.

The emissions on these tubes are representative. Figure 9 shows the locations of emission from a tube containing sources that were graded as A during the test and Figure 10 shows the pressure and cumulative event count profiles. While many tubes showed a burst of emission just above the service pressure, the source in Figure 9 became active later in the test and was concave up. The test was stopped and the pressure reduced. Emission was arrested and began again only when the pressure exceed its previous maximum. Since the count curve slope seemed to turn down upon reloading, the source was regraded to B and called for follow-up inspection.

A second and third tube which showed less copious emission but a concentrations at a particular location are shown in Figures 11 and 12. The source shown was called for follow-up inspection due to its spatial concentration and persistence throughout the test. These tubes were subsequently tested hydrostatically to 5/3 service pressure after a delay of several months and simultaneously monitored using acoustic emission. They showed emission which peaked at approximately 15.2 MPa and subsequently decayed rapidly with increasing pressure.



Starting Pressure : 628
Minimum Pressure : 0
Maximum Pressure : 5270
Total Events recorded : 841

Figure 2. Acoustic emission and pressure as a function of time for a cylinder with machined cut 0.0625" deep and 2" in length.

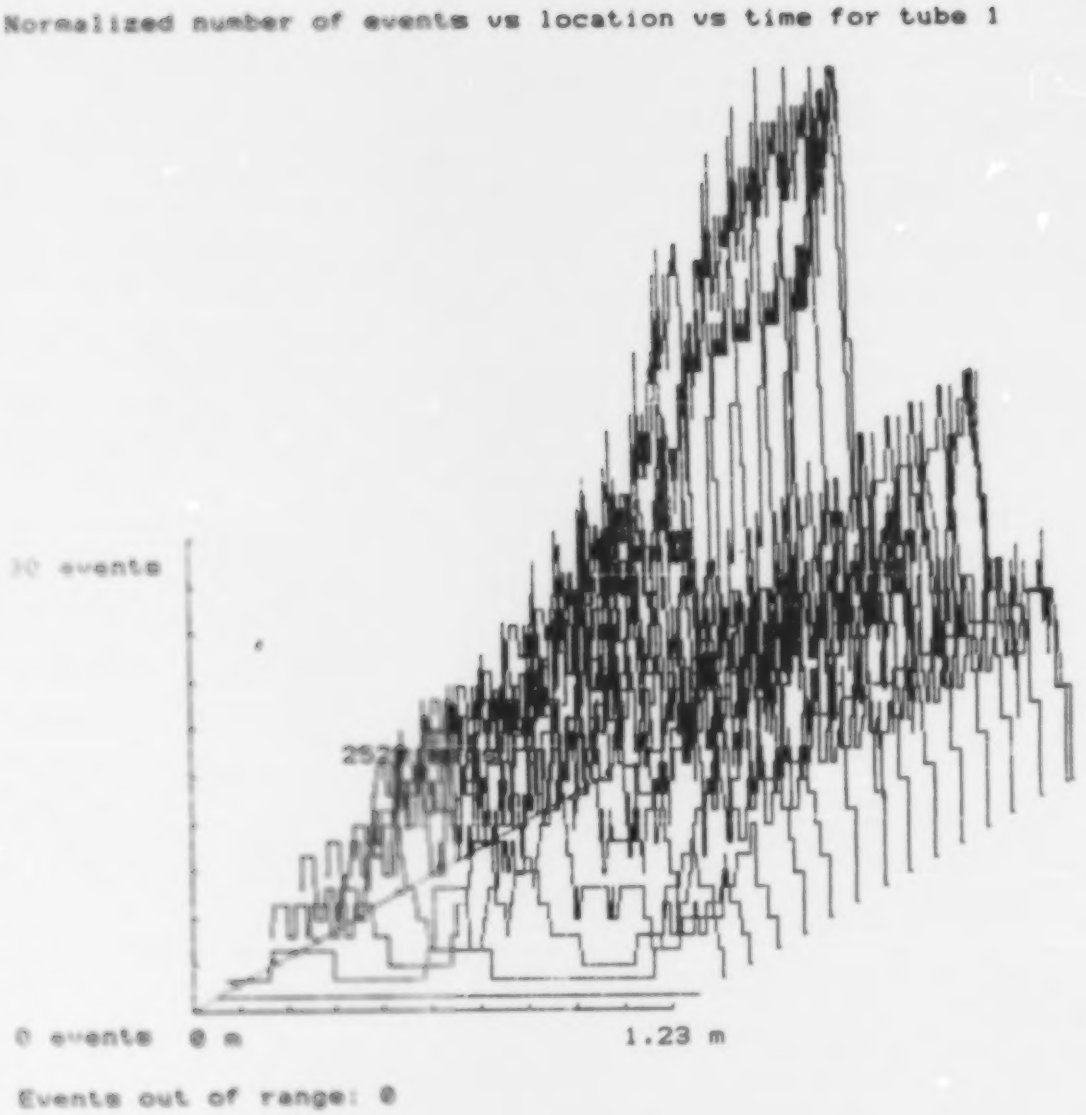


Figure 3. Acoustic emission events as a function of time and location for a cylinder with a machined cut 0.0625" deep and 2" in length.

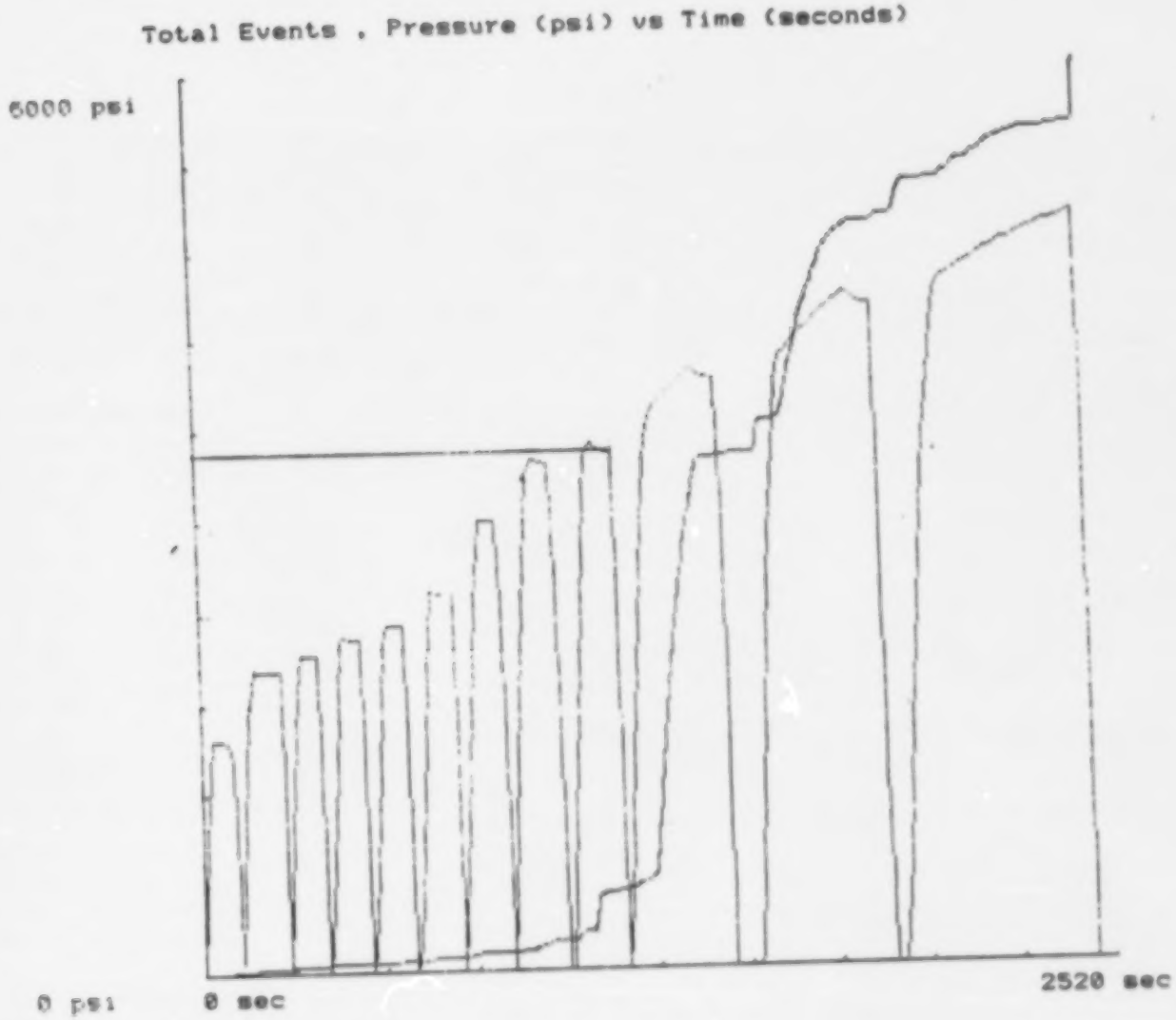


Figure 4. Acoustic emission events and pressure as a function of time for cylinder with a transverse machined cut 1.125" in depth.

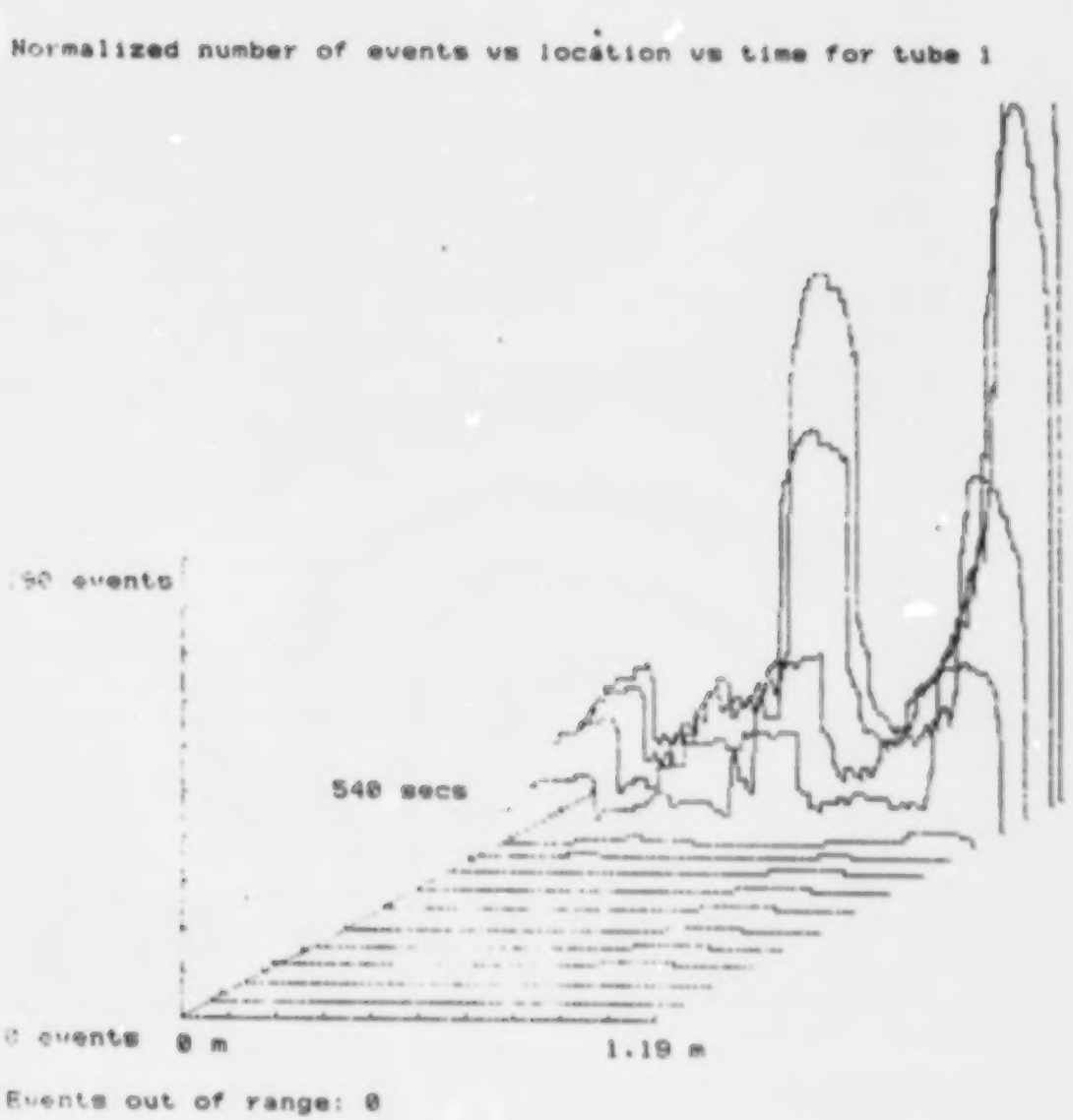


Figure 5. Acoustic emission events as a function of time and location for cylinder with three separate weld beads along the cylinder axis.

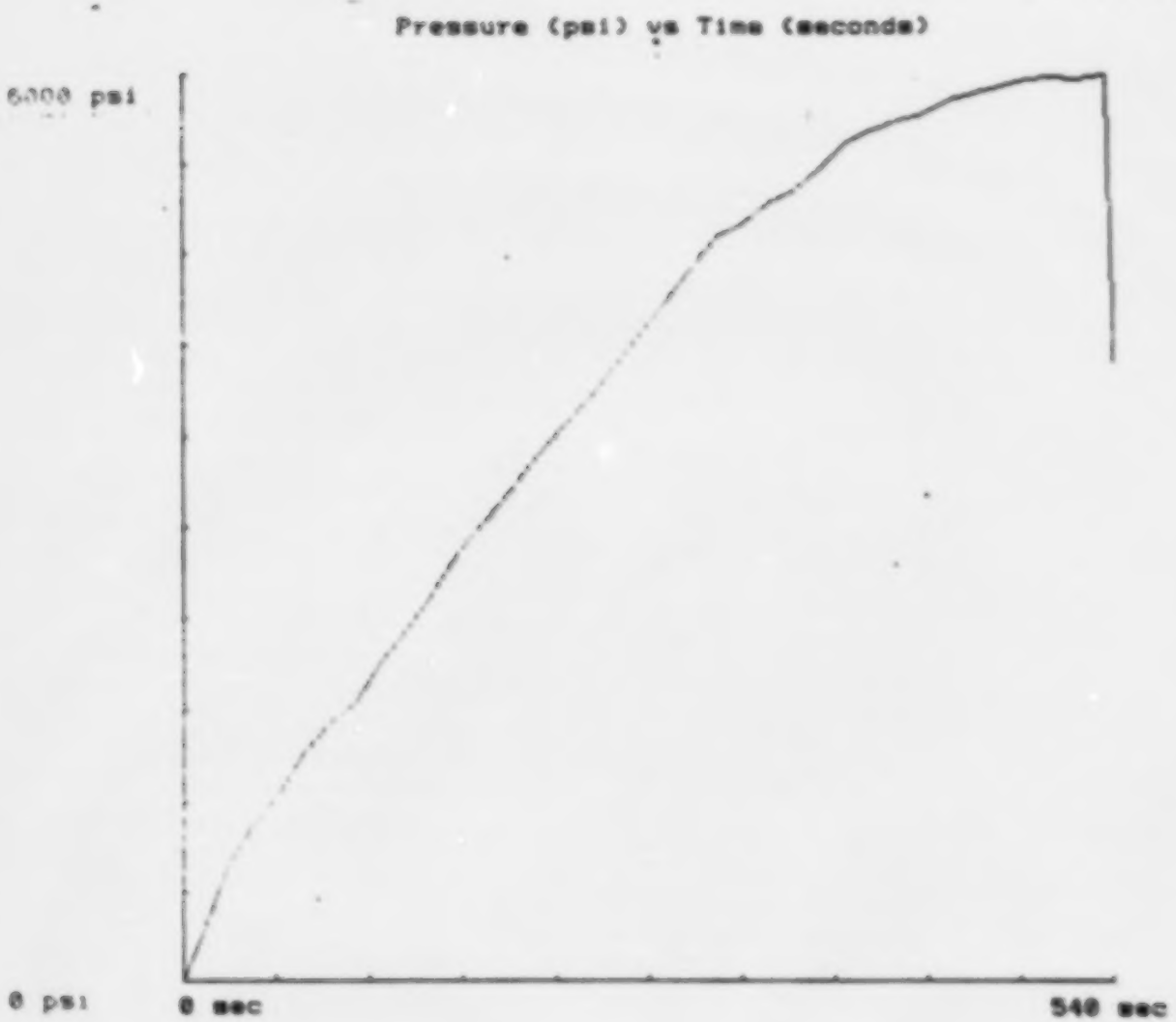


Figure 6. Acoustic emission events and pressure as a function of time for a cylinder with three separate weld beads along the cylinder axis.

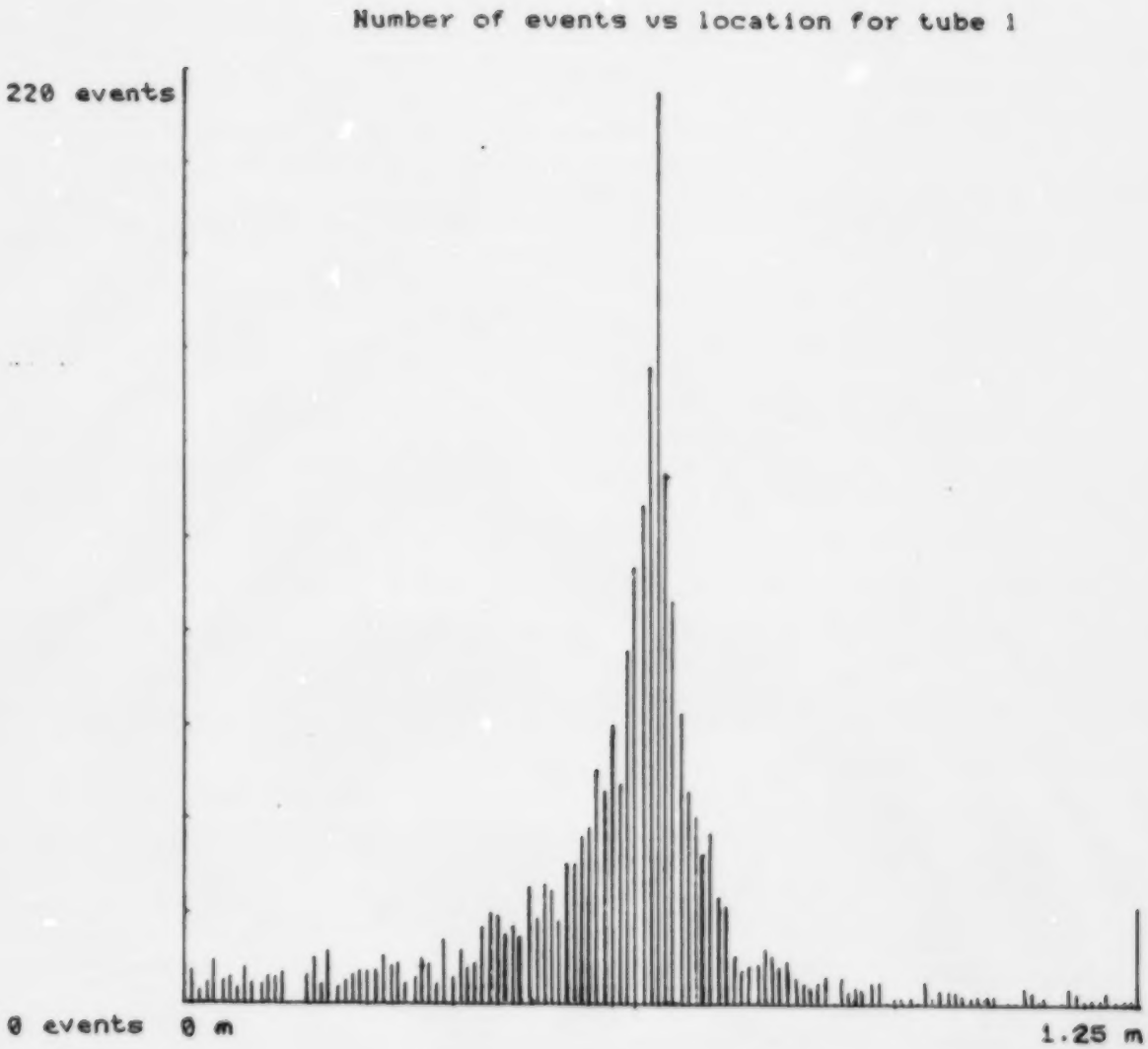


Figure 7. Acoustic emission events as a function of time and location for a cylinder with a cyclically fatigued crack.

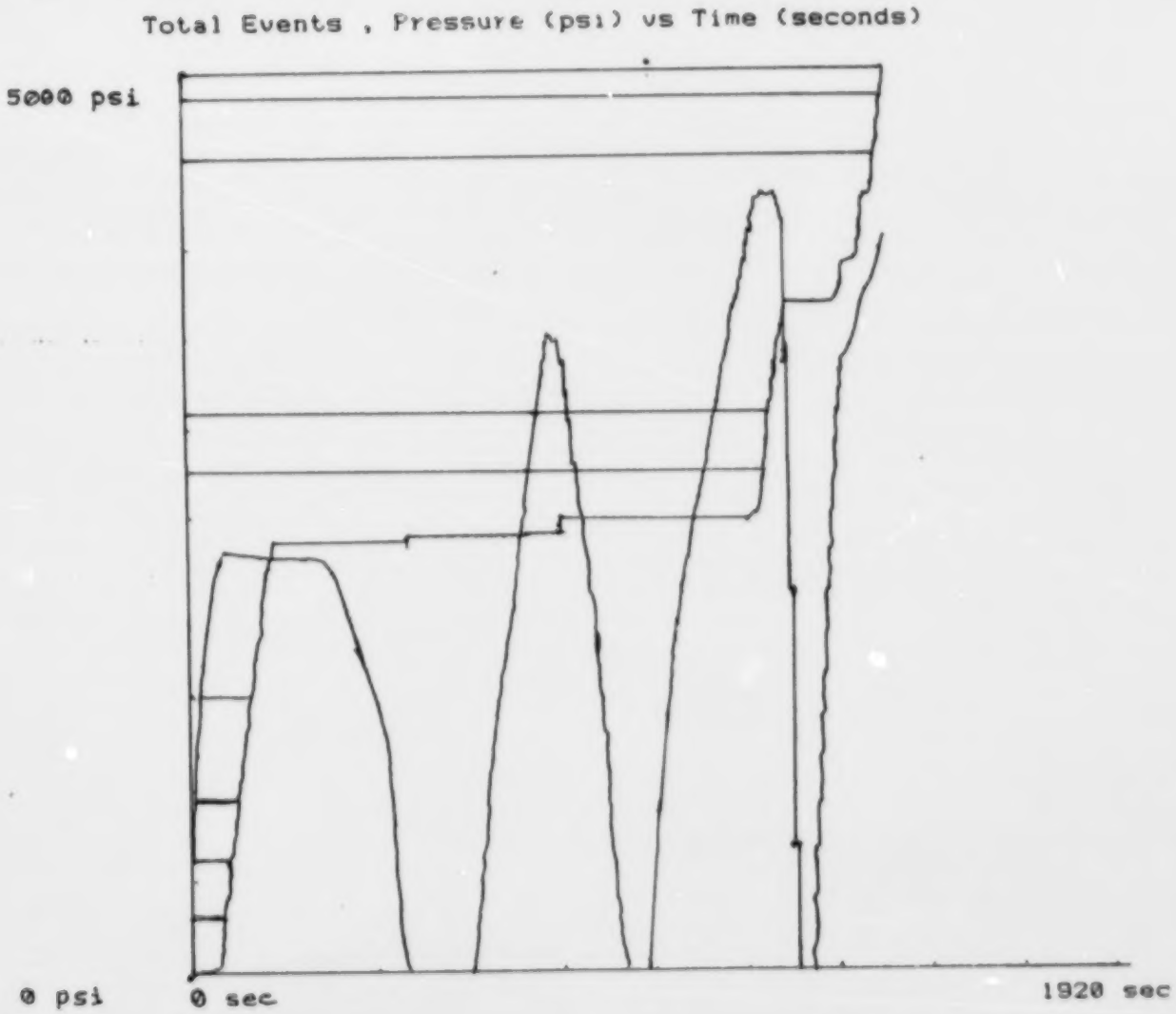


Figure 8. Acoustic emission events and pressure as a function of time for a cylinder with cyclically fatigued crack.

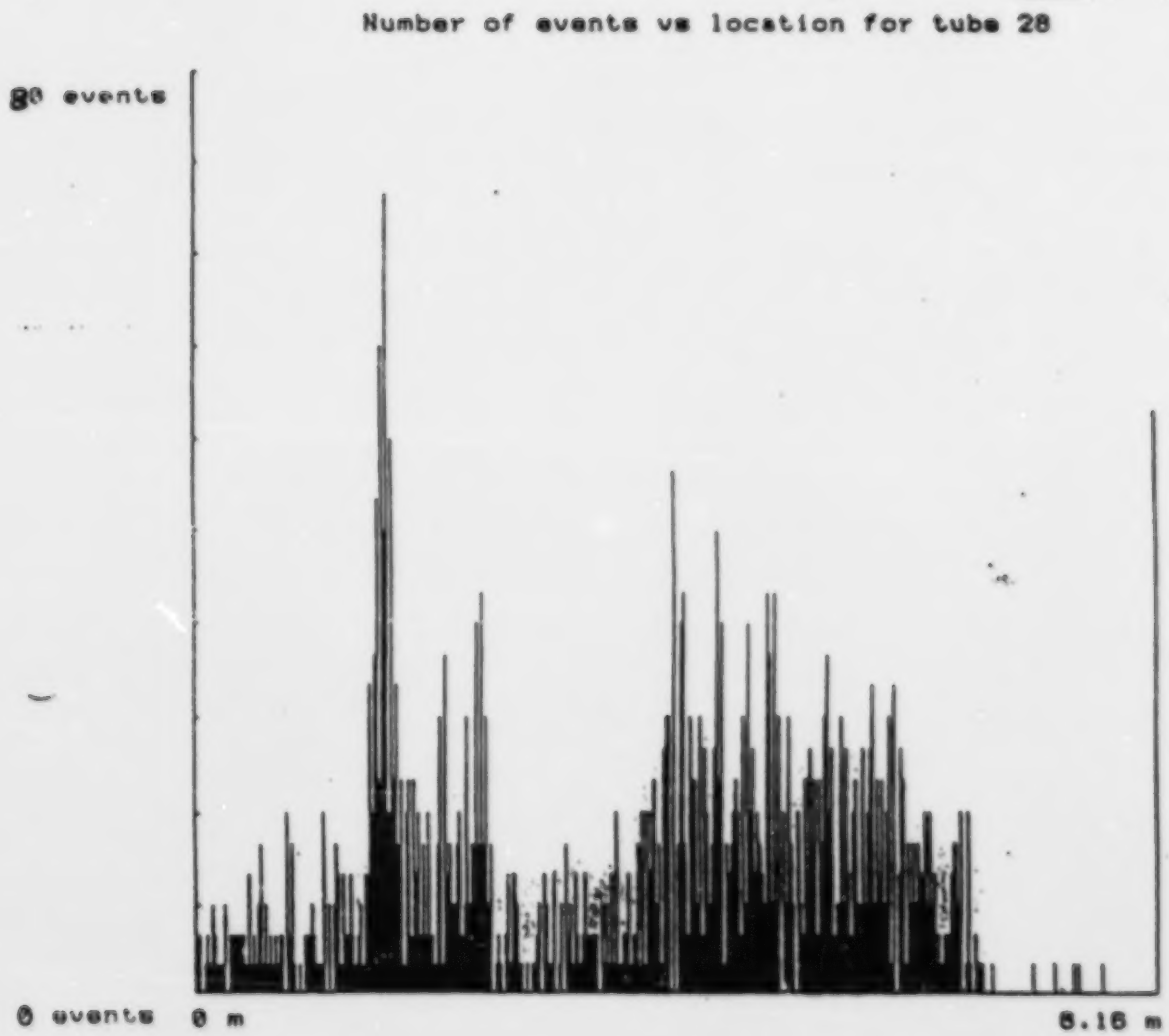


Figure 9. Acoustic emission events as a function of location for a tube mounted on a hydrogen tube trailer showing general emission with concentrations at certain locations along the length.

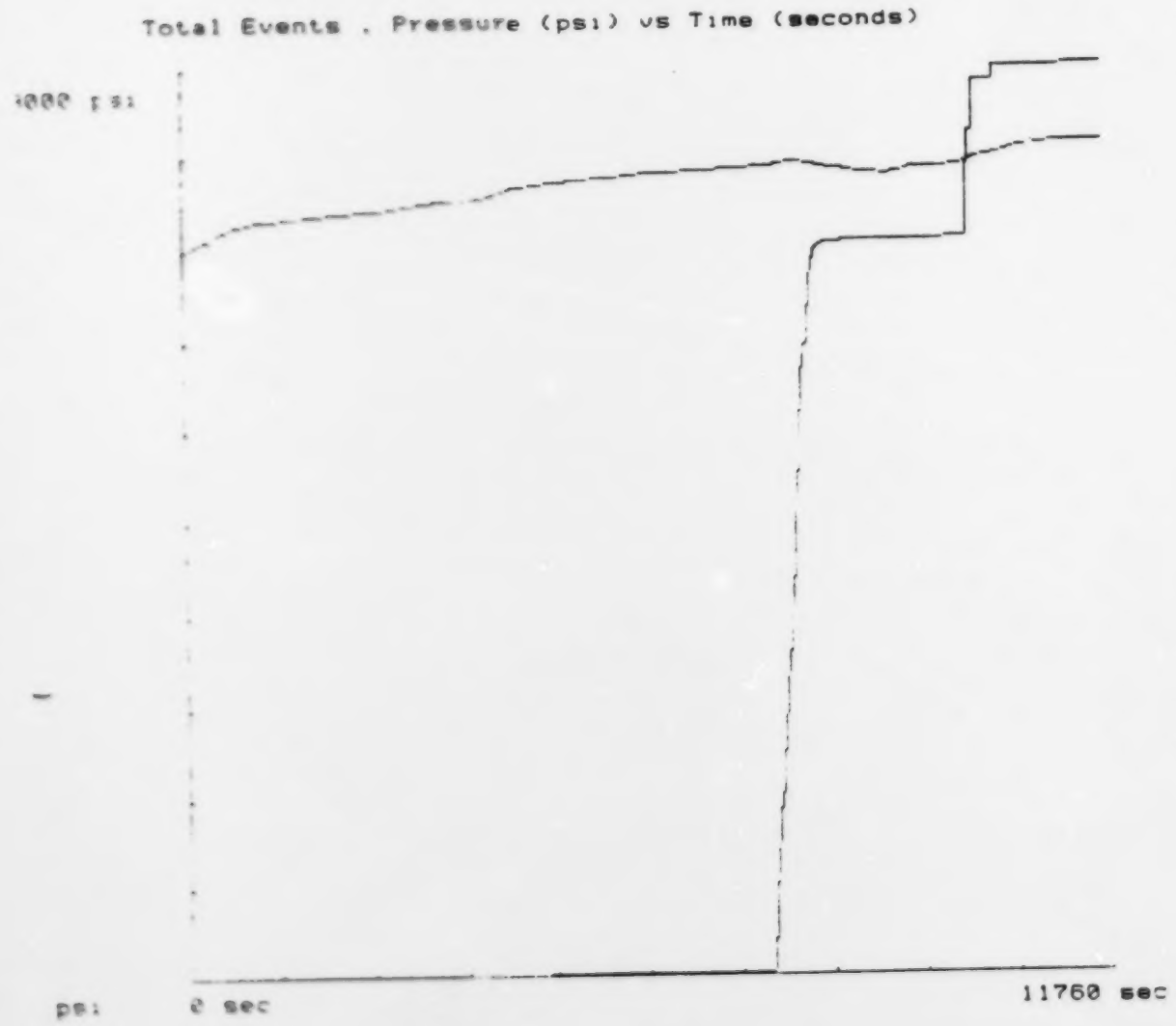


Figure 10. Acoustic emission events and pressure as a function of time for the tube in Figure 9.

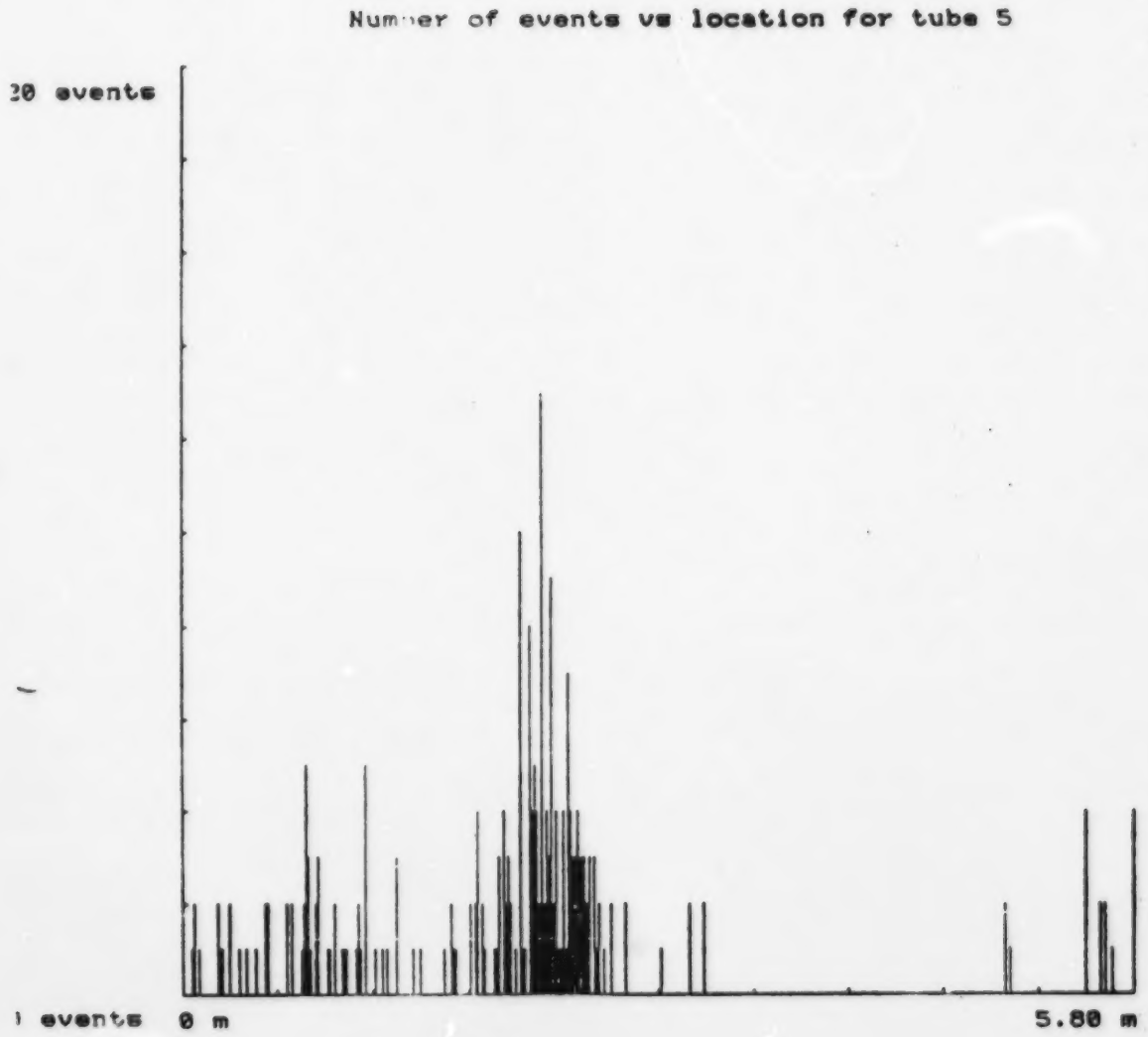


Figure 11. Acoustic emission events as a function of location for a tube mounted on a hydrogen tube trailer showing persistent localized emission.

6. DISCUSSION

6.1. Tolerable Flaw Size

Generally, no fabrication standards, codes or specifications allow crack-like defects. Cracks in these structural components are regarded as the most dangerous type of defect. While other types considered less injurious may be tolerated, most codes and standards including CTC/DOT regulations state that "no crack shall be acceptable".

At the manufacturing stage, any cylinder or tube with quenching cracks that have not been removed by machining or grinding must be rejected. Inspection methods for detection of such crack-like defects include magnetic particle, dye penetrant or ultrasonics. For the DOT-3T tubes, however, paragraph 178.45-12 from CFR Title 49 specifies that the ultrasonic equipment be calibrated to detect a notch equal to five percent of the minimum design wall thickness.

Except for Section VIII, Division 2, AF-770 which states that all forged vessels shall be free from loose scale, gouges or grooves and cracks and seams, ASME III, Appendix G bases assessment of defects on linear elastic fracture mechanics for postulated or design defects of 1/4 of the wall thickness in depth and six times the wall thickness in length. Safety factors are used in the assessment and the fracture toughness values are generally derived by correlations with Charpy V-notch or drop weight test data.

The methods of ASME XI, Appendix A to assess the significance of defects are similar to those of ASME III, Appendix G, with the difference that real rather than postulated defects are considered. Indications from ultrasonic examination are translated into simplified shapes amenable to linear elastic fracture mechanics analysis. They are thus valid for thick sections under elastic conditions. For thinner sections and for elastic-plastic conditions, these procedures will be very conservative and will predict a critical size of defect equal to or smaller than that necessary to cause failure.

A more flexible approach is assumed by the National Board Inspection Code for Pressure Vessel Inspectors. For pressure vessels where corrosion is expected during the service life, NBIC states that the type of inspection should take into account the condition of the vessel and environment in which it operates. In the case of tubes and cylinders, the experience of member companies of the Compressed Gas Association has been accepted by authorities having jurisdiction. In addition to a number of rejection criteria for wall thinning by corrosion based on remaining wall thickness and the dimensions of the corroded area, mechanical defects such as scratches, cuts and gouges are causes for rejection if the wall thickness is reduced by more than five percent. If the wall thickness is unknown, then the tube or cylinder must be rejected if the defect reduces the wall thickness by more than 1.27 mm. Failure experience showed that critical flaws were in the range of 10-20% of wall thickness (15). A value of 20% of wall thickness has been reported from linear elastic fracture mechanics calculations (16). While the fracture mechanics analysis is consistent with these observations, the LEFM approach is conservative in these ductile materials. On the other hand, a fatigue crack growth acceleration factor of 6 was used to account for hydrogen-assisted growth. The latter factor could be as high as to 15 in these materials (17). Thus, the agreement may be coincidental.

In summary, while the behavior of tubes and cylinders can be described by fracture mechanics when flaws and growth rates are well-characterized and the materials are generally flaw tolerant, experience dictates a conservative approach to any acute flaw that could propagate rapidly to failure. Tubes and cylinders are conservatively designed and generally manufactured to

consistently high quality standards. They can tolerate substantial wall thinning due to general corrosion and acceptance criteria based on experience have been established by CGA. For any more acute defect that could lead to rapid failure a conservative criteria would be five percent of wall thickness. If the flaw can be ground out, the vessel can remain in service if wall thinning remains within acceptable limits.

6.2. Inspection Requirements

Well-established quality control and inspection procedures generally assure that when a tube or cylinder enters its service life it is fit for service. Furthermore, materials selection and mechanical design and good maintenance practice resist the predictable forms of materials degradation such as general corrosion and fatigue. There remains the possibility of rare, but particularly dangerous, failure mechanisms that occur occasionally and create concern for safe operation of these vessels. Analysis of failures in tubes in service shows these rappid, rare events to be a significant cause of failure. These are time-dependent failure mechanisms whose rate of failure is increased by the presence of agressive media in the environment. Due to the speed at which failure can occur with these mechanisms and the consequences of failure, any inspection procedure must focus on detection of this type of defect. In addition, the method should detect indications of wall thinning and other normal degradation phenomena.

6.3. Acoustic Emission Behavior

Oxidation associated with wall thinning provides copious acoustic emission (18). The tests carried out in this study to date show that acoustic emission is sensitive to flaws that are in a condition to propagate. Observed behaviors ranged from indications below the service pressure in freshly created flaws, to indications which appeared only a few hundred psi before fracture. Early indications were followed by a dormant period until a sufficiently high load was reached where propagation and emission occurred continuously to failure. Cycling during the dormant period produced emissions on loading and unloading. This behavior may be explained by an initial burst due to initial crack propagation followed by friction at the crack faces (23).

The initial emission burst could arise from oxide or corrosion product cracking at the crack tip or propagation of the crack through the crack-tip plastic zone and subsequent arrest in the new ductile material. Since the emissions in the dormant period occurred at low loads when crack surfaces are likely to be in close proximity, the emission can be attributed to friction at these surfaces. Persistent emission at a particular location would confirm the presence of a crack.

Of the various parameters available for measuring acoustic emission, such as events, ringdown counts and various amplitude and energy descriptors, events are the most appropriate for these vessels. The other parameters are significantly affected by the transfer function between source and transducer which varies with the location of the source and by instrumentation gain and threshold settings. They also depend on the relative gain and threshold setting of the instrumentation. Thus, a procedure which detects and locates an event, confirms the existence of a source by location of additional events at that location would be sufficient to indicate that follow-up by other NDT inspection is required. Standard ASTM 569-82 criticality grades can be used to determine safety during the test, i.e. whether to terminate the test if the rate of emission is increasing. However, any confirmed crack (by emission on cycling and/or Kaiser effect) should be followed up. The preferred method for follow-up inspections is ultrasonic testing (16, 19, 21).

6.4. Test Results

In the fourteen tests carried out in this study to date, five of the cylinders would have been rejected by hydrotest due to bursting and would have been undetected by the water jacket test. Five of the cylinders would have been rejected by acoustic emission at an overpressure of 115% and nine at an overpressure of 5/3 of the service pressure. Among the latter nine, three would not have been detected by hydrotest but acoustic emission tests revealed they would have had experienced crack extension due to the test itself. Thus, in the case of hydrostatic tests, use of acoustic emission is strongly indicated to detect any crack extension introduced by the test. The volumetric expansion was not effective in revealing crack-like defects in these cylinders and could be replaced by acoustic emission. They are both difficult to accommodate on the same test as acoustic emission would be difficult to monitor in the water jacket.

6.5. Reliability Enhancement

It has been estimated in the literature that the probability of nondetection of small crack-like defects using hydrostatic testing is 98.% (20). The hydrostatic test reveals only those large flaws that will fail at the time of the test. It does not reveal activity associated with non-critical, but active flaws. It also introduces the possibility of introducing undetected damage into the vessel. The addition of acoustic emission testing would significantly decrease the probability of nondetection and reduce the risk of introducing undetected damage into the vessel thereby significantly increasing the reliability of the vessels. The risk of introducing environmentally-assisted deterioration due to residual water is always present with the hydrostatic test.

The probability of nondetection for a first acoustic emission test has been estimated as 1 to 10^{-2} and 10^{-1} to 10^{-2} for repeat acoustic emission inspections (20). The latter values for acoustic emission are in the range of other conventional nondestructive testing methods.

The frictional effects observed in this study have also been observed in fatigue tests. A general sensitivity to small active defects has been documented repeatedly for acoustic emission. Acoustic emission testing in service is generally carried out at low overpressures from 102% to 115%. Frictional effects in fatigue tests occur at low loads consistent with the observations in this study. The ability to detect such active defects early in their propagation cycle would increase reliability. In-situ testing with the product gas as the pressurization fluid would reduce the risk of failure due to residual water from a hydrostatic test and eliminate contamination of the product by residual water.

7. RECOMMENDATIONS

Reliability enhancements through increased flaw detectability from the use of acoustic emission are sufficiently advantageous that they should be implemented immediately. The water jacket has been shown to be insensitive to potentially dangerous flaws and serves little purpose. The hydrostatic test alone does not record potentially dangerous flaws which could prove detrimental during the interval between tests. Accompaniedby acoustic emission any pressurization above the normal service pressure would provide useful information on the existence of subcritical cracks. The accompanying economic advantages that accrue to the operators of tube trailers are sufficiently attractive that the method should be appealing to them. There are two options whereby acoustic

emission testing can be implemented. Both methods offer enhancements over the current hydrostatic test which is accompanied by permanent expansion measurements in water jacket. The option adopted by an operator would depend on his maintenance procedures and policies.

7.1. Hydrotest and Acoustic Emission

In this option, the hydrostatic test is retained and acoustic emission testing is used in lieu of the water jacket. This is an extremely conservative approach which retains the high retest pressure of the current testing procedure and simply replaces the water jacket with the more sensitive acoustic emission monitoring. Testing at 5/3 service pressure would excite activity in smaller flaws than the lower pressures in the second option outlined below and this level of test pressure, combined with considerations of crack propagation rates and crack retardation effects induced at this level of pressure provides a margin of safety consistent with a 10-year retesting interval (21).

This option thus retains the advantages of the currently mandated retest methods, namely, the "proof test" character of the hydrotest and supplements it with the additional sensitivity of acoustic emission monitoring. In the case of vessels that would be rejected by the water jacket due to in-service induced deterioration, such wall thinning is produced by corrosion where cracking of the corrosion products are readily detected by acoustic emission.

This method requires disassembly of the tubes from their trailer and does not offer the same economies that the in situ option provides. However, there are other economies since several tubes can be tested simultaneously. In addition, due to the higher sensitivity for small flaws at the higher test pressure and crack retardation that occurs at the higher test pressure, it has been proposed that the retest interval can be extended to ten years (24).

Any defects detected by acoustic emission would be subjected to ultrasonic and visual examination for confirmation and sizing, an additional inspection requirement not required at present. This proposal offers both enhanced safety and economies to the operator of the vessels and to the public.

7.2. In-Situ Acoustic Emission Testing

In this option, compressed gas tubes and cylinders would be pressurized using the product gas normally transported by the vessels as the pressurization fluid and monitored using acoustic emission. For reasons of safety and availability of pressurization pumping equipment at the filling station and the presence of overpressurization safety devices in the system, the test pressure is generally limited too 110% of normal service pressure. Pressurization would be carried out to the highest value deemed reasonable from test practicalities, namely, pressurization capabilities at the filling station and the presence of overpressurization safety devices in the system. This is of the order of 110% to 115% of the service pressure. If there have been accidental overloads or pressure excessions due to temperature cycling to pressures of 110% or over, testing under this option risks being ineffective due to the Kaiser Effect.

Since the sensitivity to smaller flaws is lower in this test option than the previous one due to the lower test pressure, this method must retain the five-year retest interval. Also the lower test pressure puts a premium on each emission event. Thus, careful attention to gains and

threshold setting is required as is interpretation of every indication. The sensitivity of this option can be significantly enhanced by cycling to detect and confirm secondary emissions which are active at low test pressures and often not masked by the Kaiser effect.

While crack-like defects should be eliminated, it has been proposed that cracks up to 20% of the wall thickness could be tolerated. However, due to the rapidity with which an environmental assist can induce propagation, removal is always the most prudent course of action.

Pressurization at these levels would produce less copious emission than at the levels proposed in the previous option. Furthermore, any acoustic emission test involves the detection of a certain amount of background noise. The use of a criterion based on the number of emissions is, at this stage of the technology, arbitrary. More experience is required with the method before such criterion can be adopted. Rather, positive procedures will be required to confirm indications as originating at flaws as opposed to noise. There are three methods to achieve such confirmation: use of the Kaiser Effect, use of source location, and use of secondary emissions. Use of these methods is common in acoustic emission monitoring of other vessels.

Each of these procedures will require pressure cycling which is more costly than a single pressurization to the maximum value and pressurization with a gas can be much slower than with water. A minimum mandated cycle would include an increase in pressure to the service pressure, a decrease to almost zero pressure and an increase to the prescribed retest pressure. Beyond the minimum mandated cycle, the test procedure should be sufficiently flexible as to permit additional cycling to permit examination of any Kaiser-related and secondary phenomenon. Test personnel should be trained to a level that permits them to use these methods to enhance flaw detectability and to confirm indications. Any indication confirmed by these methods would be called for inspection by ultrasonics and the vessel repaired or rejected if the flaw exceed acceptable limits.

7.3. Flaw Rejection Criteria

At this stage in the application of the technology, it is most prudent to assume a conservative criterion for vessel rejection. Such a criterion is normally set at an appropriate value of the remaining wall thickness. While 20% has been accepted based on fracture mechanics (16), 10% does not seem to be sufficiently conservative given failure experience in Europe (15) and 5% is called for already in CGA (22) and CFR (11,12) specifications. An acceptable approach would be to retain the experience-based criteria set down by the CGA and to not accept any crack-like flaw that cannot be ground out leaving sufficient wall thickness to meet CGA requirements. This criteron could apply to both testing options described above.

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